NASA TECHNICAL NOTE

NASA TN D-5214

c. 1

NASA TN D-5214

LOAN COPY: RETURN TO
AFWL (WLIL-2)
KIRTLAND AFB, N MEX

TECH LIBRARY KAFB, NM
0131986

CHARACTERIZATION OF PRESSURE PERTURBATIONS INDUCED IN A ROCKET COMBUSTOR BY A MACHINE GUN

by Daniel E. Sokolowski, David W. Vincent, and E. William Conrad

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1969

TECH LIBRARY KAFB, NM

0131986

CHARACTERIZATION OF PRESSURE PERTURBATIONS INDUCED IN A ROCKET COMBUSTOR BY A MACHINE GUN

By Daniel E. Sokolowski, David W. Vincent, and E. William Conrad

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

The purpose of this experimental study was to develop a new explosive device for use in rocket combustor stability rating tests and to evaluate the performance of the device over a wide range of operating conditions. Evaluation tests were conducted with two different liquid propellant combinations at chamber pressures up to 300 psia (2070 kN/m^2 abs) and thrusts up to 20 000 pounds (89 kN). Results proved that a 30-caliber machine gun was successful in perturbing the combustion environment and in many cases initiated high-frequency combustion instability. Characteristics of explosively induced pressure perturbations were related to operating conditions of the gun and combustor. It was concluded that inducing a perturbation through a single port as compared with a multiport bomb ring enhanced the ability to interpret the measured perturbation characteristics.

CONTENTS

CHARACTERIZATION OF PRESSURE PERTURBATIONS INDUCED IN A ROCKET COMBUSTOR BY A MACHINE GUN

by Daniel E. Sokolowski, David W. Vincent, and E. William Conrad

Lewis Research Center

SUMMARY

High-frequency combustion instability is a recurrent problem in rocket engine development programs. Many previous investigations of the problem relied on several stability rating techniques to initiate the unstable processes. Two commonly used techniques are (1) ramping downward the hydrogen injection temperature of the hydrogen-oxygen propellant combination until combustion instability is triggered and (2) using an explosive device to perturb the combustion processes until combustion instability is initiated.

Explosive rating devices employed in the past generally have been expensive in terms of testing time. Frequently, because of poor quality control of the explosive, inadequate instrumentation, and changing geometrical relation between explosives and instrumentation, considerable scatter of data and a general inability to make quantitative comparisons between investigations resulted. Also, the interrelations between rating techniques have not been established.

To minimize some of these shortcomings, a new explosive rating device was sought wherein a series of low-cost, finely graduated explosive charges could be introduced through a single chamber port, time-consuming manual reloading between tests could be avoided, and adaptability to flight-type engines would be improved. The criteria for such a device were essentially met by a machine gun firing blanks.

Using a modified 30-caliber machine gun with blank cartridges containing several charge sizes to perturb the combustion media, successful initiation of high-frequency combustion instability was attained. Propellant combinations of earth storable (N_2O_4/50 percent UDMH-50 percent N_2H_4) as well as hydrogen-oxygen were used at chamber pressures up to 300 psia (2070 kN/m^2 abs) and thrusts up to 20 000 pounds (89 kN). Because of the single port of injection, pressure perturbation pulse amplitudes and shock wave transit times were very reproducible and could be related to operating conditions of the gun and combustor. Comparisons are made between the results from (1) the machine gun and multiport type of rating devices and (2) the machine gun and temperature ramping techniques.

INTRODUCTION

The phenomena of high-frequency combustion instability is a recurrent problem in rocket engine development programs. Because of the frequency range of pressure oscillations within the combustion chamber, the phrase "acoustic mode combustion instability" is perhaps more fitting. In many past investigations of the problem, several stability rating techniques were used to initiate the unstable processes. For example, when hydrogen and oxygen are the propellants being burned in the combustor, a temperature ramping technique is often used (ref. 1). In this case, the injection temperature of the hydrogen is ramped downward during a single test until combustion instability is triggered. With most other propellant combinations, the explosive rating technique is used (refs. 2 to 6). Here, explosive devices are used to induce perturbations into an operating combustion chamber. Depending on the perturbation characteristics (for example, pressure amplitude and velocity), the disturbance may trigger combustion instability or dampout.

Explosive devices may be either directionally or nondirectionally oriented. Most flight-type rocket engines are stability rated using nondirectional explosives which are usually suspended within the combustion chamber and electrically detonated. On the other hand, research- and development-type programs generally use explosive devices which are directionally oriented. The chamber location of a directed explosive device may bias the tangential, radial, or longitudinal modes of combustion instability (ref. 5). Characteristics of a directionally oriented perturbation are more easily related to the explosive characteristics (such as, charge size and rate of reaction) as well as the operating conditions within the combustor. Nondirectional explosives present an unknown role of the bomb case strength which may be changed in the combustion medium by such processes as ablation. Further discussion of the variables which influence the characterization of a pressure perturbation may be found in reference 6. Because of the advantages of directionally oriented explosive devices, the availability of improved devices for use with flight-type engines would be of value.

Many of the explosive rating devices employed in the past were expensive in terms of testing time. Furthermore, poor quality control of the explosive and inadequate instrumentation frequently resulted in both considerable scatter of data and a general inability to make quantitative comparisons between various investigations. At present, better quality control and more sophisticated instrumentation are being used (refs. 4, 7, 8, and 9) which will hopefully improve the quality of reported data. In investigations such as those reported in references 2 and 3, the stability of many injector or thrust chamber configurations was evaluated. In these particular investigations, the use of a multiport chamber ring, containing a given number of explosive charges which could be fired consecutively with increasingly larger charge sizes during a single test, provided some

improvement in economy of operation. However, the following shortcomings were still present:

(1) Lack of accessibility around the engine resulted in the use of only four explosive charges per test and, consequently, rather large graduations between charge sizes.

(2) The explosives were fired at different circumferential locations with respect to injector and baffle patterns.

(3) Shutdown time between tests to reload the explosive device was longer than desired.

(4) Adaptability of a multiport ring to chambers other than those having a heat-sink design still remained doubtful.

(5) Quantitative information which could shed more light on the interaction of the pressure perturbation with the combustion processes could not be obtained because of the limited amount of instrumentation used for each test as well as the geometrical relation between explosive and instrumentation ports.

To minimize these shortcomings, a new explosive device was sought where a series of low-cost, finely graduated charges could be introduced through a single chamber port, time consuming manual reloading between tests could be avoided, and adaptability to flight-type engines would be more promising. Consideration was given to various mechanical charge indexing devices which would seal against chamber pressure. It became evident that the criteria for such a device were essentially met by a machine gun using blank explosive cartridges of graduated charge sizes.

Accordingly, a 30-caliber machine gun was procured from the United States Air Force. Because the barrel discharges into a high pressure region (combustion chamber), it was necessary to alter the operating mechanism of the gun. Described herein are the modifications found necessary as well as quantitative results obtained during a series of experiments. Tests with the machine gun were initially conducted with an earth storable (N_2O_4/50 percent UDMH-50 percent N_2H_4) propellant combination. For comparative purposes, a few tests were conducted using the multiport bomb ring. The machine gun was further evaluated in a combustor using the hydrogen and oxygen (H-O) propellant combination. Again for comparative purposes, the hydrogen injection temperature was ramped downward in some of these tests. The storable propellant rocket engine operated at 100 psia (690 kN/m^2 abs) and yielded 6700 pounds (29.8 kN) thrust, while the hydrogen-oxygen (H-O) rocket engine operated at 300 psia (2070 kN/m^2 abs) and yielded 20 000 pounds (89 kN) thrust.

APPARATUS

COMBUSTOR

All experiments were conducted using a heat-sink-type combustor made from mild steel. Internal walls of the combustion chamber and nozzle were coated with 0.012 inch (0.03048 cm) of flame-sprayed nichrome, which acted as a bonding agent, and 0.018 inch (0.04572 cm) of zirconium oxide to reduce heat transfer. The cylindrical chamber diameter was 10.77 inches (27.36 cm), characteristic length was 42 inches (106.68 cm), and chamber contraction ratio was nominally 1.89. Two propellant combinations were used. The first propellant combination was nitrogen tetroxide (N_2O_4) and a blend of 50 percent unsymmetrical dimethyl hydrazine (UDMH) and 50 percent hydrazine (N_2H_4) burned at 100-psia (690-kN/m^2 abs) chamber pressure and yielding 6700 pounds (29.8 kN) thrust. Thrust per element (fuel-oxidant-fuel triplet) was nominally 74 pounds (0.3292 kN). The second propellant combination was hydrogen and oxygen burned at 300-psia (2070-kN/m^2 abs) chamber pressure and yielding 20 000 pounds (89 kN) thrust. In this case, thrust per element (concentric tube) was nominally 48 pounds (0.2135 kN).

STABILITY RATING TECHNIQUES

A 30-caliber machine gun (NATO design) was used as the device for most of the stability rating tests. Modifications of the gas operated bolt to convert the gun to a rating device are described in detail in the appendix.

TABLE I. - CHARACTERISTICS OF EXPLOSIVES

[From ref. 13]

Type of explosive	Density, g/ml	Rate of reaction, m/sec	Brisance (sand test), g	Heat released, cal/g	Gas released,[a] ml/g
Black powder	1.60	400	6.3	665	280
Lead azide	4.00	5100	16.7	367	308
TNT	1.56	6900	47.5	925	730
Nitrocellulose (13.3 percent N_2)	1.20	7300	48.7	965	883
Nitroglycerin	1.60	7700	58.7	1486	715
Cyclotrimethylenetrinitramine (RDX)	1.70	8350	59.0	1300	908
Pentaerythrite tetranitrate (PETN)	1.70	8300	61.2	1385	790

[a]At temperature of 0° C and pressure of 1 atm.

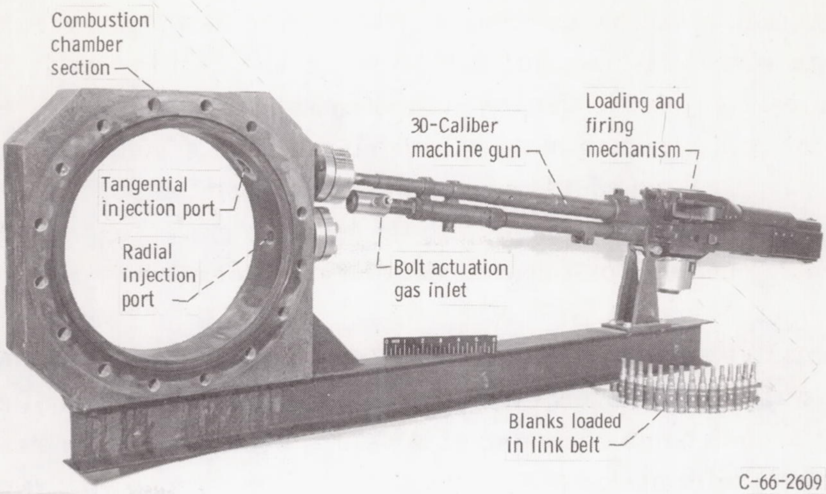


Figure 1. - Machine gun rating device mounted tangentially to combustion chamber section.

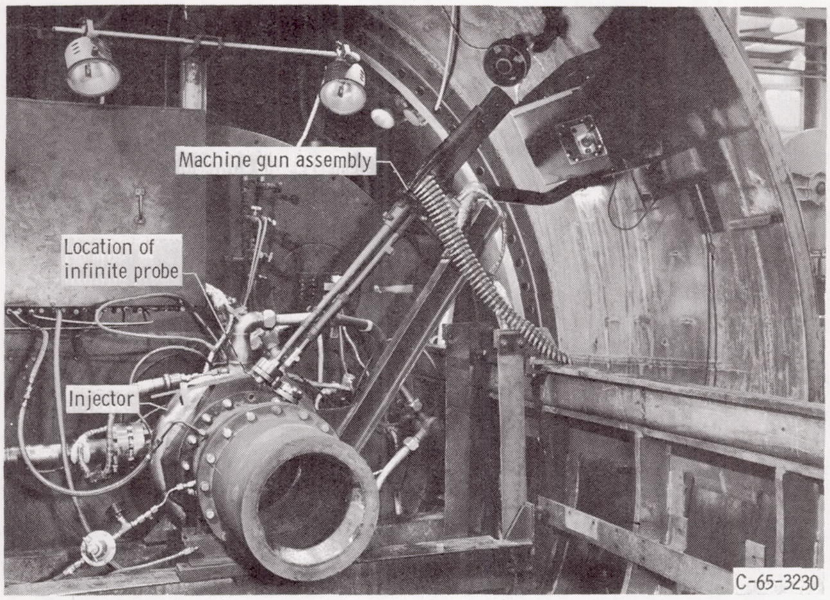


Figure 2. - Test cell with combustor and machine gun rating device assembly.

The explosive used in the blank cartridges was a single base, tubular type made by Dupont (SR 4759) and consisted mostly of nitrocellulose. A comparison between this explosive (hereafter referred to as nitrocellulose) and other common explosives is shown in table I. Eight graduations in explosive charge size were achieved by varying the amount of nitrocellulose in the cartridges from 18.5 to 39.0 grains (1.3588 to 2.527 g). An array of explosive cartridges—usually from the smallest to the largest charge size—for each test were fed to the gun via a standard link belt.

The machine gun, mounted in the tangential port of a special chamber section, is shown in figure 1. The gun could be moved from a tangential port to a radial port. A typical arrangement of the combustor with the machine gun rating assembly attached is shown in figure 2. The link belt shown contains enough explosive cartridges for at least several tests.

For comparative purposes, a bomb ring (ref. 2) having four tangentially oriented bombing ports was used in several tests. The bomb ring is shown in figure 3. The explosive used in each bomb consisted of tablets of cyclotrimethylenetrinitramine (RDX) with pentaerythrite tetranitrate (PETN) as the initiator. Bomb size varied from 1.6 to 45.2 grains (0.1037 to 2.9489 g). During a typical test, increasingly larger bomb sizes were successively detonated from bomb ports P1 to P4 as shown in figure 3.

The machine gun and bomb ring are two specific devices categorized under the explosive rating technique. A nonexplosive technique commonly used to rate the stability

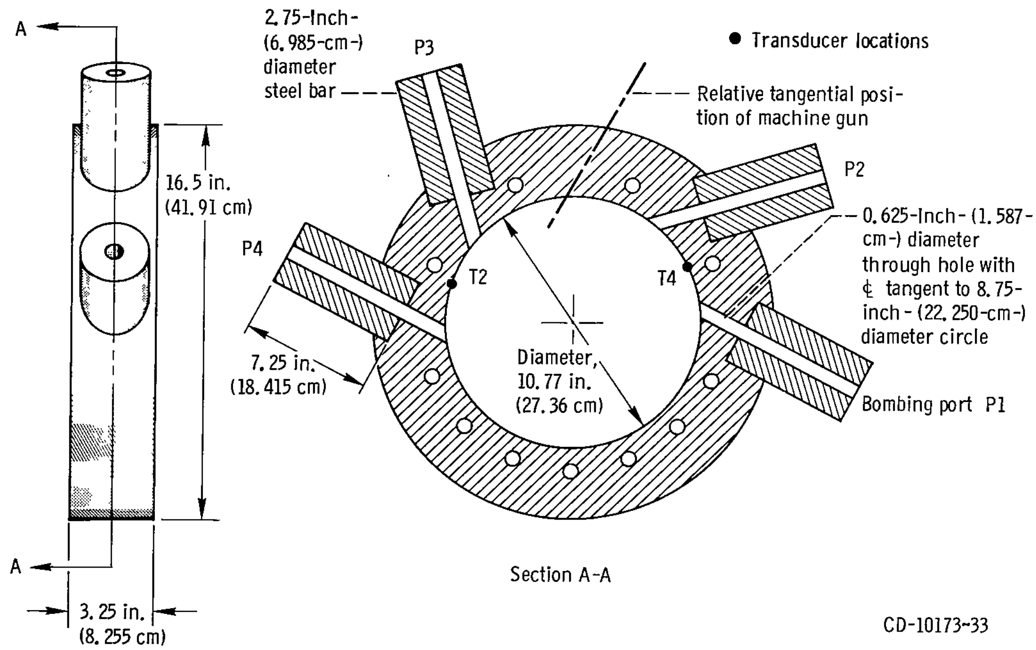


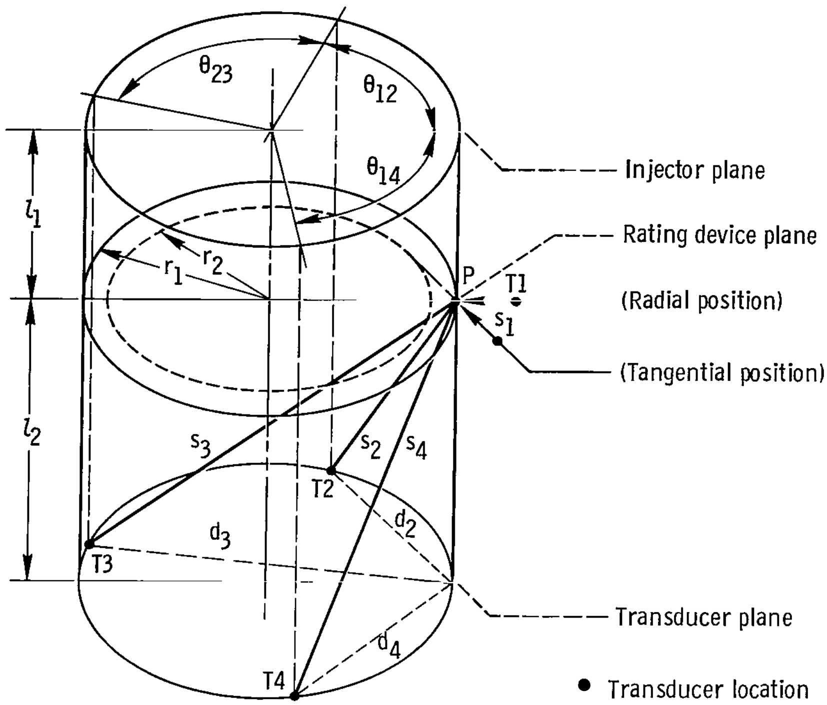
Figure 3. - NASA Lewis bomb ring.

of rocket combustors using a hydrogen-oxygen propellant combination is to ramp the hydrogen injection temperature downward in a single test until acoustic mode combustion instability is initiated (ref. 1). A mapping of the stability boundary for a specific combustor configuration is accomplished by varying the operating conditions (such as, oxidant-fuel ratio or chamber pressure) of the combustor between tests. The temperature difference between a given stable operating condition and the stability boundary is normally termed the hydrogen injection temperature (HIT) margin. Thus, the higher the HIT margin for any test, the greater the degree of stability.

INSTRUMENTATION

Both low- and high-frequency response types of instumentation were used. Low-frequency measurements, such as, mean chamber pressure, propellant flow rates, thrust, temperatures, and injector manifold pressures were recorded with standard instrumentation. High-frequency measurements, namely chamber pressure oscillations, were measured by high-frequency, piezoelectric pressure transducers. Such transducers, housed in water-cooled jackets and flush mounted, had a frequency response flat to 6000 hertz and resonant frequency of 20 000 hertz. The transducers were not shock mounted. However, acceleration compensation enabled the transducers to have a shock sensitivity of only 0.001 psi/G (0.006895 $kN/m^2/G$). Placement of the three to four transducers was always at a constant position with respect to the rating device for each series of tests. Locations of the high-frequency transducers are shown in figure 4.

Transducer T1 was positioned near the end of the machine gun barrel either 2.25 or 3.30 inches (5.715 or 8.382 cm) from the inner wall of the combustion chamber depending on the port orientation used. This tranducer was considered a reference, because a pressure perturbation at this location was at the boundary of the combustion region. As a consequence, the pressure perturbation would be expected to be unaffected by secondary reactions (chemical augmentation, ref. 2). On the other hand, it seems reasonable to expect that some properties of the combustion region—such as, density—would affect the pressure perturbation amplitude even at the boundary (ref. 10). Because of the dimensions of the gun barrel, a standard high-frequency transducer could not be flush mounted at position T1. Accordingly, an infinite-probe-type transducer (ref. 11) was mounted to a pressure tap which was made in the gun barrel. Briefly, the infinite probe consisted of a very long piece of tubing capped at one end and fitted with a special coupling at the other. This coupling, which housed a high-frequency transducer, was then connected to the pressure tap. The operation of an infinite probe is as follows: A pressure wave passes the transducer as it propagates down the tubing until its



	Storable tests	Hydrogen-oxygen tests
Axial distance, in. (cm)		
l_1	1.625 (4.127)	1.625 (4.127)
l_2	5.375 (13.653)	5.375 (13.653)
Radial distance, in. (cm)		
r_1	5.38 (13.665)	5.42 (13.767)
r_2	4.10 (10.414)	------------
Angular displacement, deg		
θ_{12}	59.5	78.8
θ_{23}	112.5	112.5
θ_{14}	75.5	56.3
Chordal distance, in. (cm)		
d_2	5.34 (13.564)	6.87 (17.449)
d_3	10.73 (27.254)	10.78 (27.36)
d_4	6.59 (16.739)	5.10 (12.954)
Propagation distance, in. (cm)		
s_1	3.30 (8.382)	2.25 (5.715)
s_2	7.58 (19.253)	8.73 (22.174)
s_3	12.01 (30.505)	12.05 (30.607)
s_4	8.50 (21.590)	7.41 (18.821)

CD-10174-33

Figure 4. - Combustor transducer locations.

amplitude is attenuated to such a degree that reflected waves from the capped end are negligible. Because of the attenuation before the wave passes the transducer, the measured pulse amplitudes at position T1 as reported herein are estimated to be about 70 percent of the actual value.

PROCEDURE

TESTS

A typical rocket engine test run consisted of three basic periods. The first period, called ignition, is the time from engine ignition until all starting transients settled out. The next period, lasting about 3 seconds, was termed steady state. All data of interest were recorded during this time. Engine shutdown was the final period.

During the steady-state phase, a preselected number of explosive cartridges were set off in a consecutive manner by the machine gun. This is illustrated in figure 5 where the pseudo chamber pressure history during a typical run is presented. Several resultant pressure perturbations following each explosion are shown including a perturbation which initiated instability. During a normal test, six to eight increasingly larger size charges were fired at nominally 0.3-second intervals regardless of which charge initiated instability. To decrease downtime between runs, a preprogrammed belt of cartridges was loaded before a given series of runs.

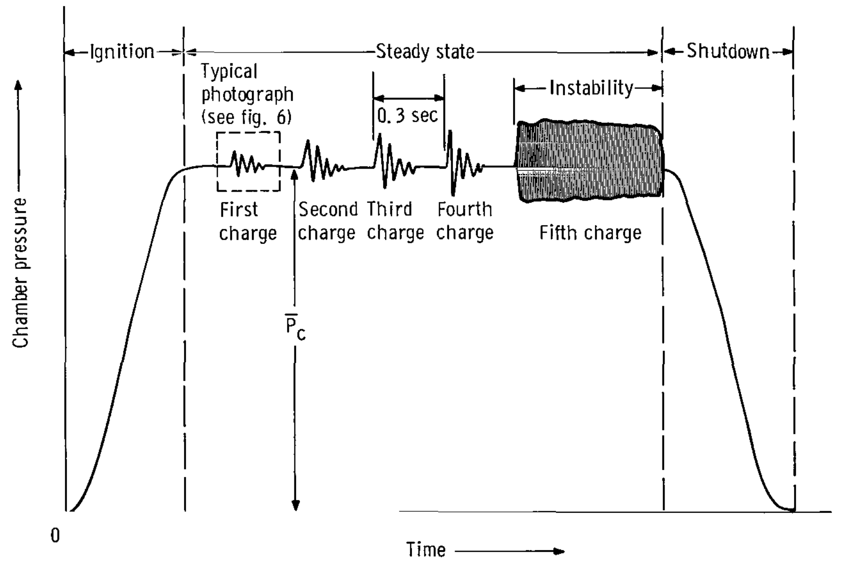


Figure 5. - Total chamber pressure history of typical test run.

DATA RECORDING AND RETRIEVAL

Low-frequency signals were digitized and recorded on magnetic tape. The digitized data on this tape were then fed into a high-speed, digital computer and reduced by a special computer program. Data were printed in 0.02-second increments. All high-frequency signals were FM recorded on magnetic tape at 60 inches per second (152.4 cm/sec) along with dc step run identifying markers and charge firing markers, as well as a standard 1000-hertz time code. The data retrieved from these latter tapes were the pressure history for each perturbation as recorded at each transducer location. The technique used to retrieve this information was as follows: All data as recorded on magnetic tape for each run were retrieved by a tape reproducer operating at $7\frac{1}{2}$ inches per second (19.05 cm/sec). The reproduced signals were then amplified and recorded by an oscillograph running at 8 inches per second (20.32 cm/sec). This then enabled manual reading of the exact time at the initial part of each perturbation. Also, the overall appearance of the data was examined for noise or faulty transducers. Next, each pressure perturbation history was recorded on fast developing, high-speed film. This was accomplished by programming the exact time for each disturbance into an electronic time code interpreter and function controller. When the tape was again replayed at a reduced speed, the time code interpreter read the time on the tape and compared it with the programmed time. When the two times were within 0.001 second, a signal from the function controller pulsed the single sweep of an oscilloscope. A camera with an open shutter and mounted on the screen of the scope recorded the trace on film. All pertinent information, such as, initial pulse amplitude, maximum pulse amplitude, and pressure rise rate of initial pulse amplitude were manually read and recorded from each picture. Time differences between initial pulses of a reference transducer and other transducers were also read from the pictures. The time code was used to correlate the low- and high-frequency measurements. Other parameters of interest, such as the total time to damp and fundamental frequency of the pressure oscillation, were harder to measure in raw form. Filtering was tried to condition this phase of the data. However, problems inherent to all filters when used with nonperiodic signals arose and so far has prevented further meaningful signal conditioning.

RESULTS AND DISCUSSION

PERTURBATION CHARACTERIZATION

A common denominator among the many types of explosives is the size of the dis-

turbance which results from releasing the potential energy of the explosive by application of a suitable initial impulse. The most readily obtained measurement of this disturbance, or perturbation, is that of the pressure. The analysis of the effects of this pressure perturbation on a system being perturbed should begin with a characterization of an ideal perturbation followed by possible causes for deviations from the ideal. With this in mind, the following discussion will (1) point out some of the ideal characteristics of an explosively induced pressure perturbation and some possible causes for deviations, (2) present several examples of typical pressure perturbations observed under different conditions, and (3) indicate the rationale for measuring only specific pressure perturbation characteristics.

Characteristics of an Explosively Induced Pressure Perturbation

By definition (ref. 12), an explosive is "a substance which, when subjected to heat, impact, friction, or other suitable initial impulse, undergoes a very rapid chemical transformation, forming other more stable products entirely or largely gaseous, whose combined volume is much greater than that of the original substance." During the chemical transformation or reaction, a specific amount of energy is released. The amount released is dependent on both the chemical composition of the explosive and the mass reacted. The rapidity of the transformation or the rate of reaction is dependent on the following:

(1) Chemical composition
(2) Geometry of the individual grains
(3) Resistance of the cartridge to explosive deformation
(4) Packing density
(5) Pressure
(6) Initial grain temperature

While the energy (heat) released from an explosive may be referred to as the total work capacity, the rate of release of this work capacity or power is commonly referred to as the brisance. Various tests, such as the sand test, have been devised (ref. 13) and have shown a direct relation between the rate of reaction and brisance (see table I). In essence, brisance is the shattering power of an explosive and is the principal means for distinguishing between the so-called low- and high-explosives.

The resultant effect of the formation of gaseous products following transformation of an explosive is an increase in the local pressure level near the explosive. Normally, the rate of reaction is so great that the rate of pressure increase results in the formation of a thin film boundary between the gaseous products and surrounding environment. The high temperature of the gaseous products, which result from the exothermic reaction,

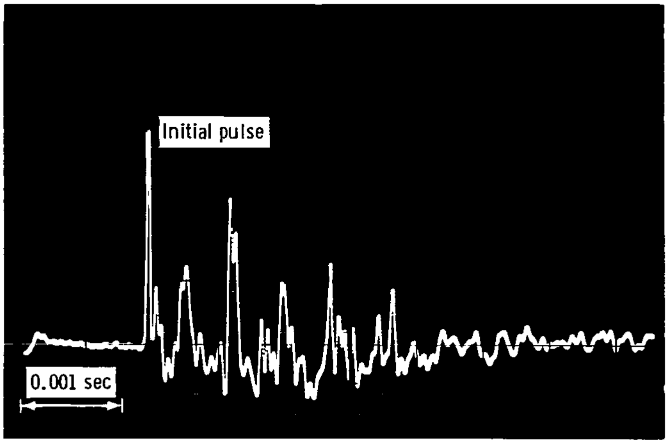
causes the gases to expand behind the thin film boundary and accelerate until speeds equal to or greater than the speed of sound are attained. At this point, the thin film boundary may properly be termed a shock front (ref. 12). Furthermore, under certain conditions, this front may change into that of a detonation (ref. 14).

Ideally, the pressure history near the source of an explosion is that of a transient disturbance which has a steep-fronted initial pressure pulse (shock front) followed by an exponentially decaying amplitude (pressure train). The amplitude of the initial pulse increases with the energy released from the explosive. The rate of pressure growth of the initial pulse is directly proportional to the rate of reaction and thus is a measure of the brisance. Finally, the decay rate of the pressure train, or the total decay time if this rate is not constant, is influenced greatly by both the type and size of the explosive charge as well as the properties of the medium in the initially perturbed volume.

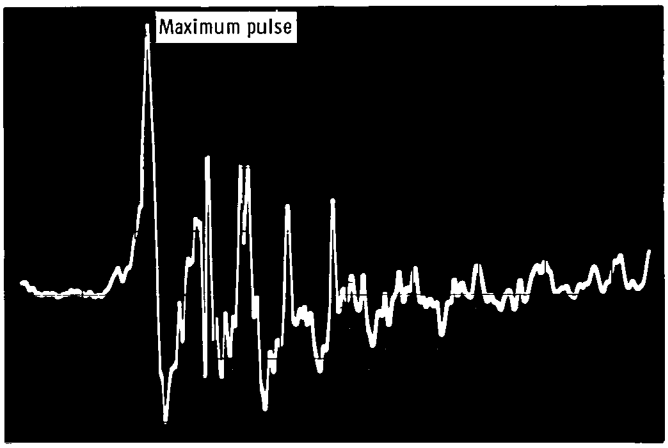
While the previous discussion pertained to the mechanisms of an explosion and the characteristics of the resulting disturbance as observed near the explosion source, consideration should be given to possible changes in the characteristics as the disturbance or perturbation propagates away from the source. With this in mind, the first apparent deviation will be noted if the shock front is traveling through a medium having liquid jets or droplets of combustible material. In references 15 and 16, it was noted that in such a medium the detonation front breaks up the liquid into smaller droplets which are thrown into the reaction zone following the front. Because of the increased surface area of these droplets, a much more rapid reaction results. This reaction change may then add more energy to the detonation-like front, thereby increasing its amplitude. Conversely, if no droplets are in the medium, no energy will be added to the front, and as a consequence, the amplitude will be attenuated with time. Other deviations result when the shock front or the pressure train following the front incurs irregularities along its boundaries; in this case, the smooth exponential decay will be altered. Reflections of the shock front from surfaces which it may encounter may be seen as oscillations in the pressure train. Another consequence of reflections is that the maximum amplitude pulse may not be necessarily the initial pulse but occur, instead, at some random time later. Finally, if some physical device—such as an orifice or a check valve—is inserted between the explosion source and the medium being perturbed, the characteristics of the pressure history will be altered greatly. In fact, the shock front may be reduced to a high-amplitude pulse having only a slight rate of pressure growth. Hence, the resultant effect on the medium through which it passes is entirely changed.

Examples of Typical Pressure Perturbations

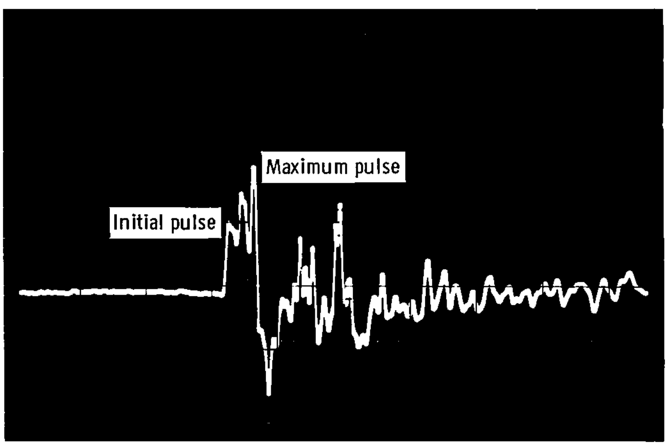
As previously discussed, the pressure history of each disturbance as observed at



(a) Pressure perturbation having initial pulse.

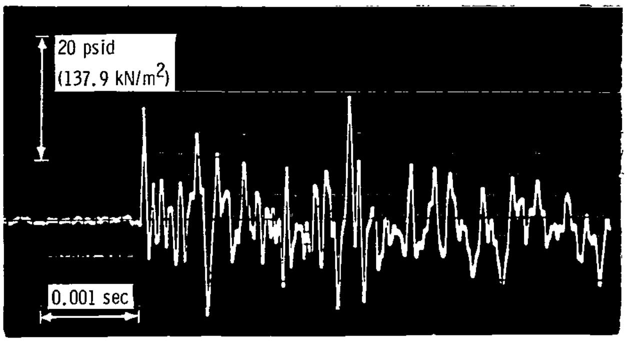


(b) Pressure perturbation having maximum pulse.

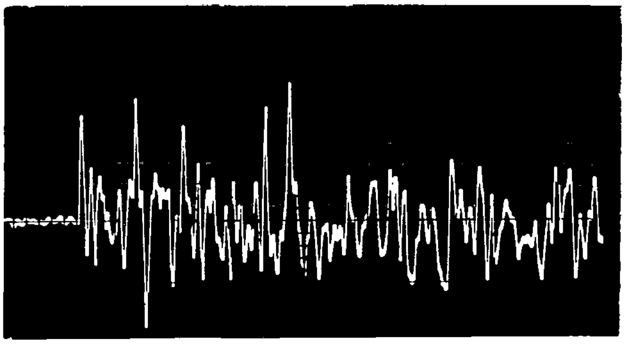


(c) Pressure perturbation having initial and maximum pulses.

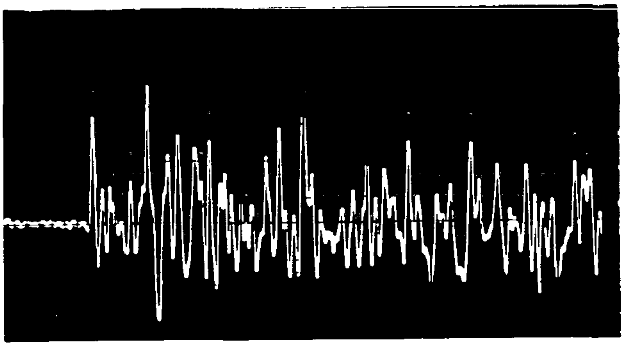
Figure 6. - Typical pressure perturbation histories.



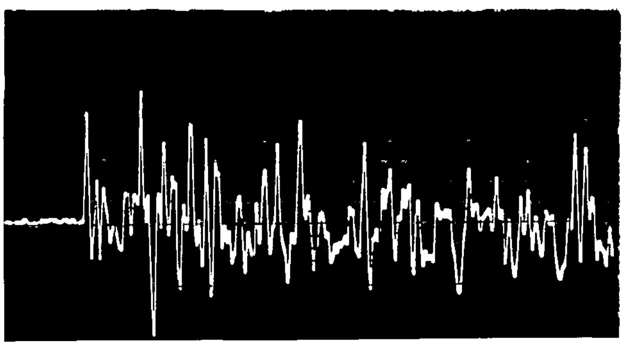
(a-1) First charge.



(a-2) Second charge.

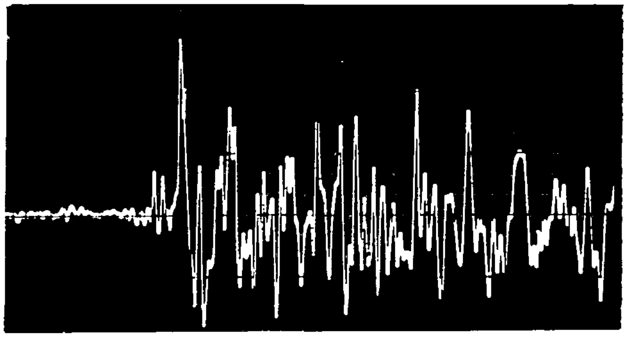


(a-3) Third charge.

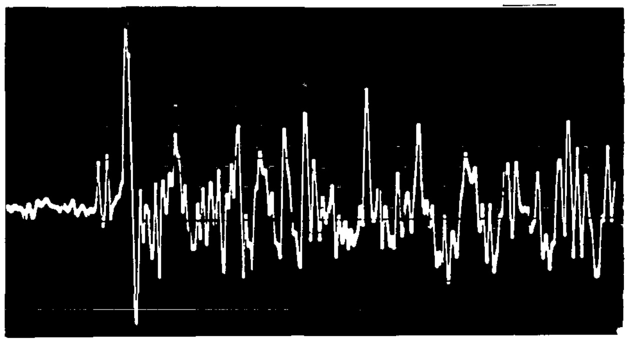


(a-4) Fourth charge.

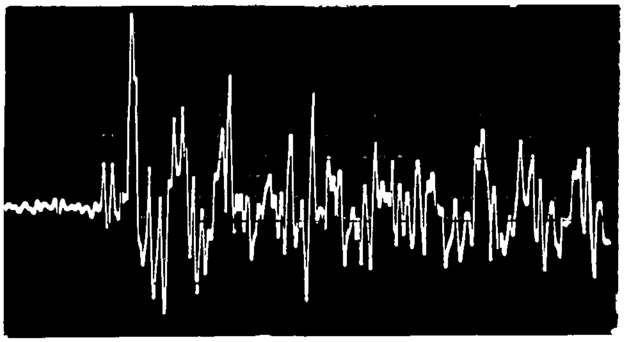
(a) Transducer location T2.



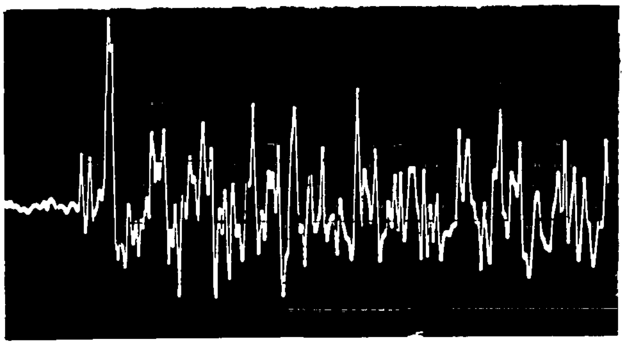
(b-1) First charge.



(b-2) Second charge.



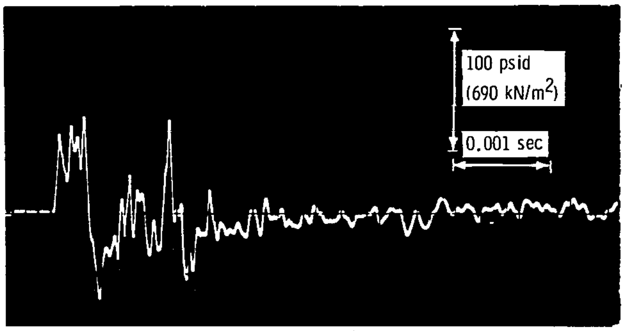
(b-3) Third charge.



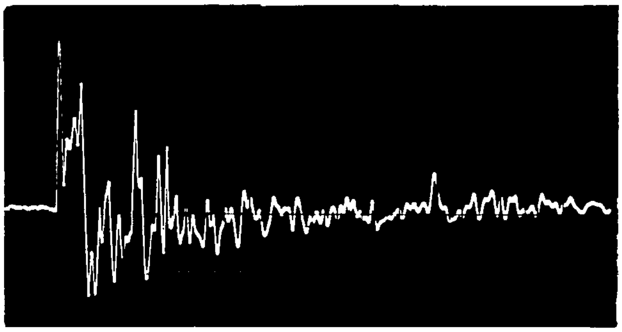
(b-4) Fourth charge.

(b) Transducer location T4.

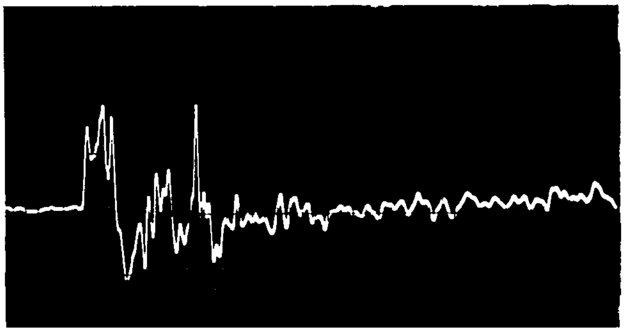
Figure 7. - Typical pressure histories of successive perturbations induced tangentially by machine gun in capped combustion chamber pressurized to 100 psia (690 kN/m^2 abs) with helium. Charge size, 39.0 grains (2.527 g).



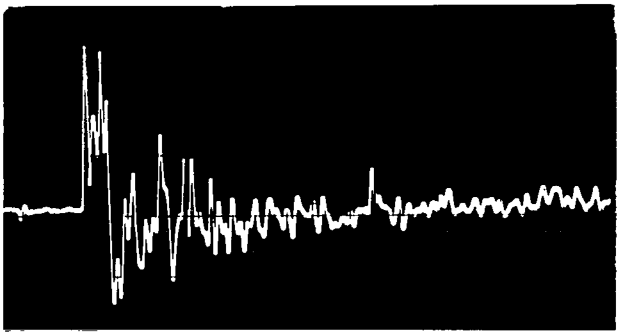
(a-1) First charge (36.5 grains or 2.365 g).



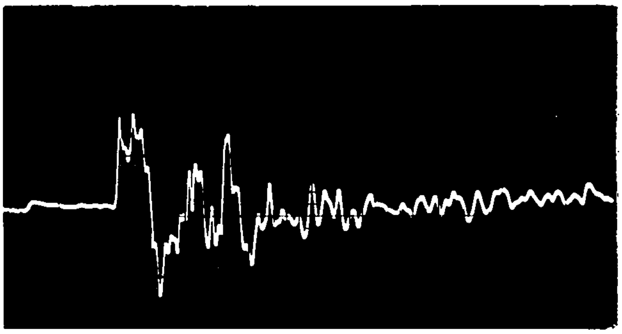
(b-1) First charge (36.5 grains or 2.365 g).



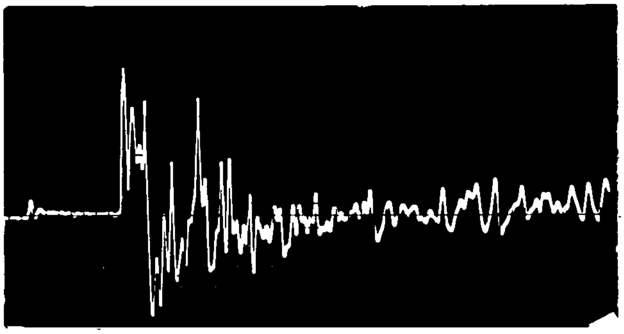
(a-2) Second charge (36.5 grains or 2.365 g).



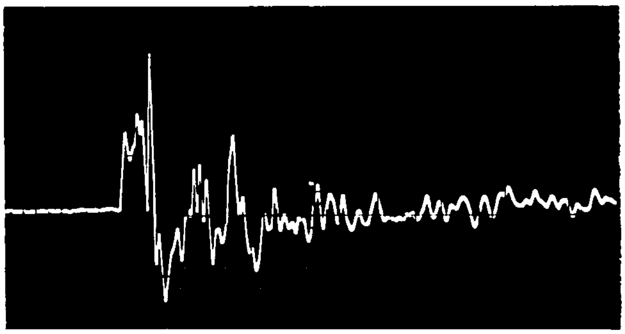
(b-2) Second charge (36.5 grains or 2.365 g).



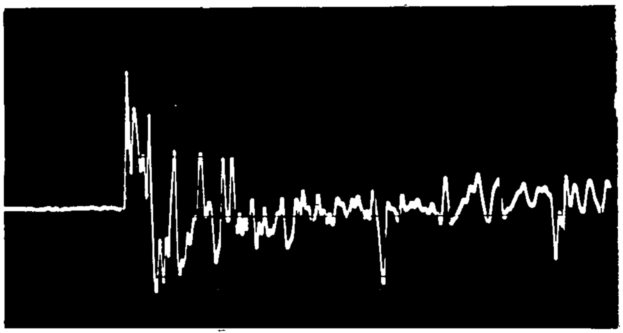
(a-3) Third charge (39.0 grains or 2.527 g).



(b-3) Third charge (39.0 grains or 2.527 g).



(a-4) Fourth charge (39.0 grains or 2.527 g).



(b-4) Fourth charge (39.0 grains or 2.527 g).

(a) Transducer location T2.

(b) Transducer location T4.

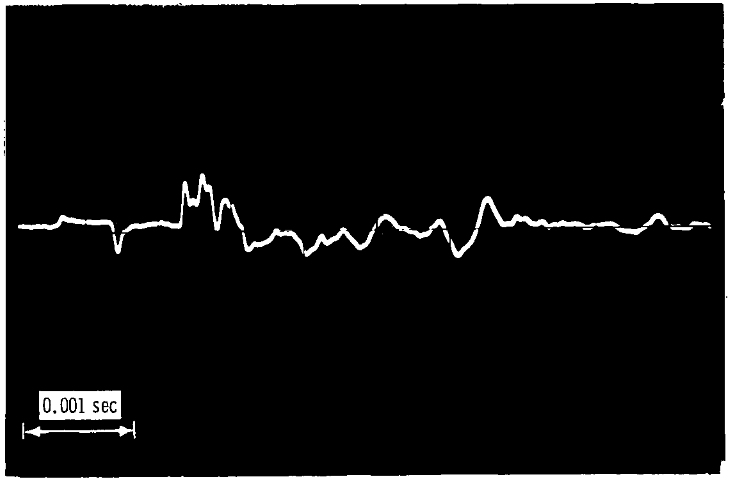
Figure 8. - Typical pressure histories of successive perturbations induced tangentially by machine gun in combustor burning storable propellant combination.

each transducer location was recorded on film by a camera which recorded the trace from the screen of an oscilloscope. The photos which are presented in this section exhibit (1) some of the notable pulse characteristics of various perturbations, (2) the repeatability of initial pulses in both inert gas as well as hot combustion tests, (3) the initial pulse amplitude increase as a perturbation travels through a region containing combustible droplets, (4) the pressure history characteristics of perturbations observed in a system with and without a check valve, and finally (5) some typical perturbations induced by the explosive RDX using the bomb ring.

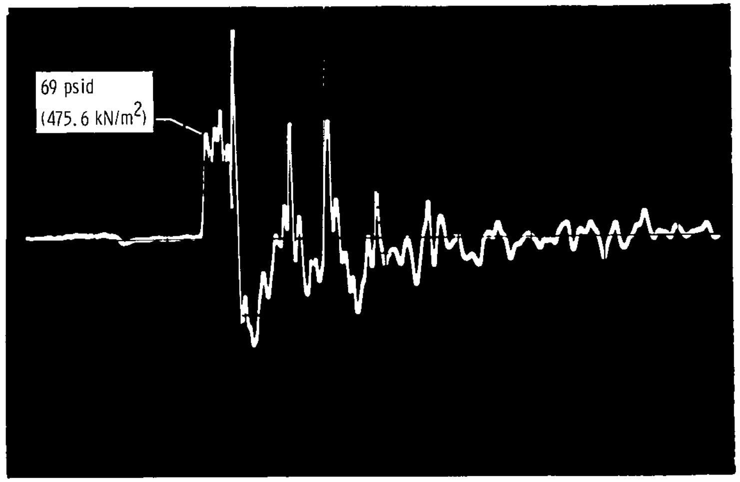
Typical pressure histories of perturbations induced by the machine gun are shown in figure 6. Figure 6(a) shows a high amplitude initial pulse or spike followed by a train of decaying amplitude pulses. Figure 6(b) shows a perturbation in which there is no distinct initial pulse and, consequently, has been labeled as having a maximum amplitude. Finally, figure 6(c) shows a perturbation which has a definite initial spike followed by pulses of increasing amplitude.

Several tests were conducted in which the machine gun was fired from a tangential position into a capped chamber pressurized to 100 psia (690 kN/m^2 abs) with helium (which simulated the speed of sound in combustion gases). Typical pressure histories of successive, explosively induced perturbations in the chamber are shown in figure 7. Figure 7(a) shows the disturbances as observed at location T2 (see fig. 4) while figure 7(b) shows the same disturbances as observed at location T4. Repeatability of the initial amplitudes is seen by comparing histories at either location. Differences in the pressure histories of a single perturbation as observed at the two locations are quite evident.

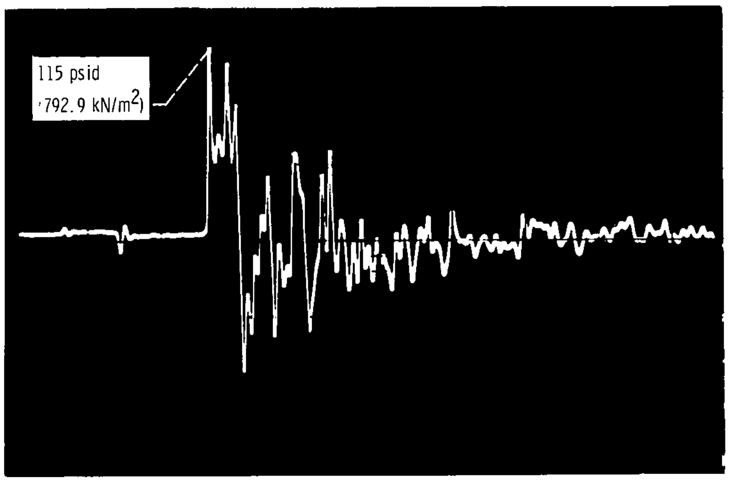
With an uncapped combustion chamber and the same rating device arrangement used in the helium gas tests, a series of tests was conducted in which the storable propellant combination (N_2O_4/50 percent UDMH-50 percent N_2H_4) was burned at 100 psia (690 kN/m^2 abs). Typical pressure histories of successive, explosively induced perturbations in the chamber are shown in figure 8. These are perturbations which did not initiate combustion instability. Figure 8(a) shows the disturbances as observed at location T2, while figure 8(b) shows the same disturbances as observed at location T4. As with the helium gas tests, reproducibility of the initial pulse amplitudes is seen by comparing successive pressure histories at either location. Differences in the pressure history of a perturbation resulting from a single charge as observed at the two locations are again quite evident. Comparing pressure perturbation characteristics between the helium gas and combustion tests reveals that (1) the pressure train decay times of a perturbation propagating in a combustion medium were much less than those in an inert medium and (2) the initial pulse amplitudes as observed at location T2 were about four times greater in the combustion tests if using the same charge size. This latter fact is probably due to the chemical augmentation of the storable propellants.



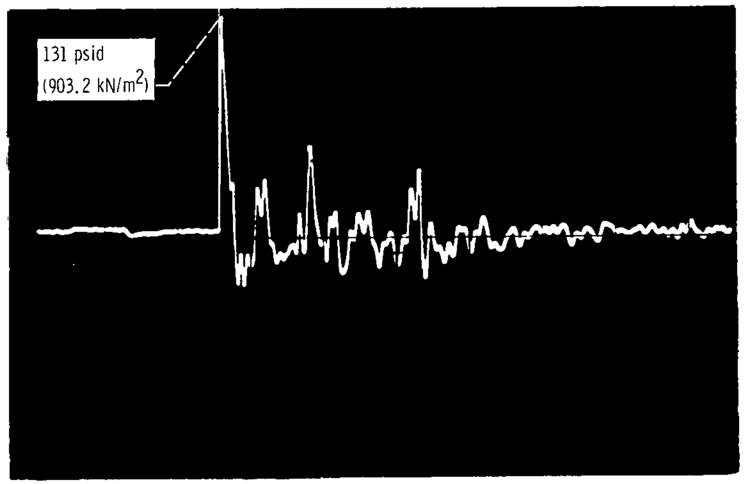
(a) Transducer location T1.



(b) Transducer location T2. Propagation distance, 10.88 inches (27.635 cm).

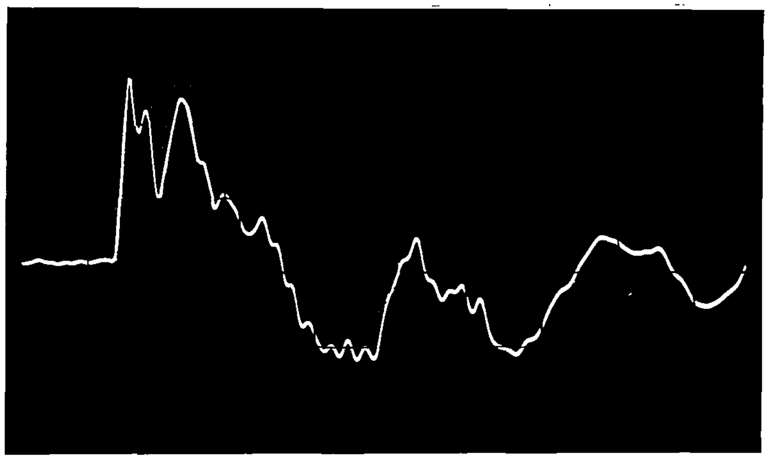


(c) Transducer location T4. Propagation distance, 11.80 inches (29.972 cm).

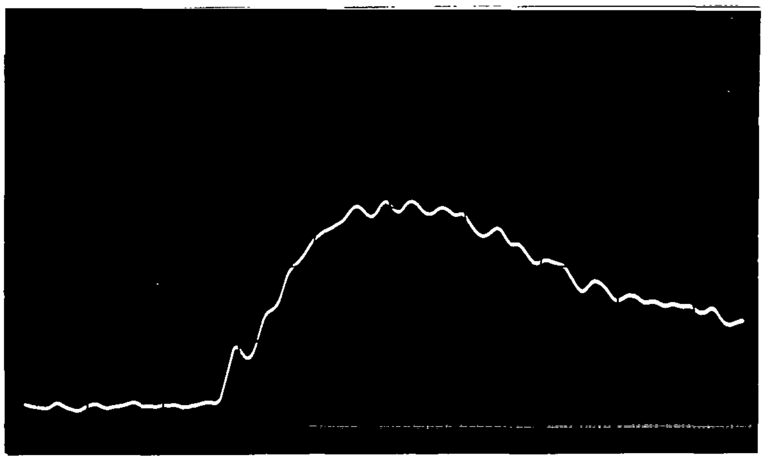


(d) Transducer location T3. Propagation distance, 15.31 inches (38.887 cm).

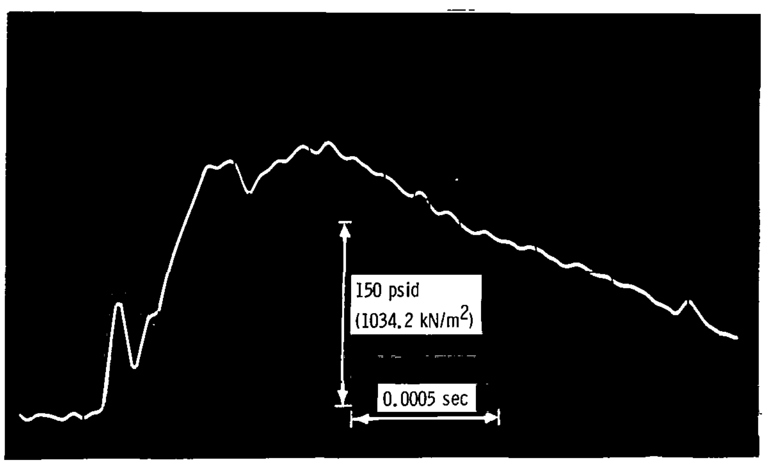
Figure 9. - Typical pressure histories of perturbation traversing combustion chamber burning storable propellant combination at 100 psia (690 kN/m^2) abs). Charge size, 30.5 grains (1.976 g) nitrocellulose induced tangentially with machine gun. (Propagation distance is shortest distance between transducer T1 in end of gun barrel and other transducers located in chamber - see fig. 4.)



(a) No check valve. Chamber pressure, 100 psia (690 kN/m^2 abs).



(b) Check valve 1; poppet mass, 43.4 grams. Chamber pressure, 300 psia (2070 kN/m^2 abs).



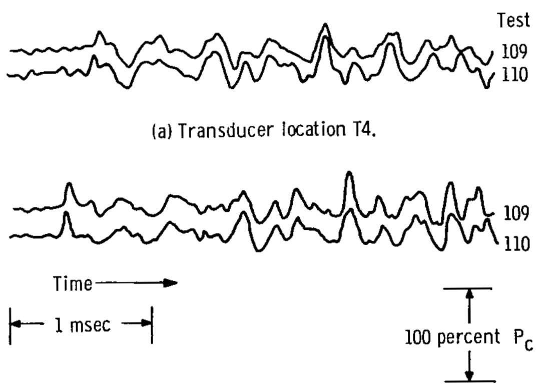
(c) Check valve 2; poppet mass, 12.5 grams. Chamber pressure, 300 psia (2070 kN/m^2 abs).

Figure 10. - Typical pressure perturbation histories as observed at transducer location T1 with and without a check valve in gun barrel. Charge size, 30.5 grains (1.976 g) nitrocellulose.

Characteristics of a perturbation as it traverses a combustion chamber burning the storable propellant combination are shown in figure 9. The growth in the initial pulse amplitude with propagation distances traveled is shown in figures 9(a) to (d). The stated distances in figure 9 correspond to the shortest distance between transducer T1 in the gun barrel and the transducers in the combustion chamber (see fig. 4).

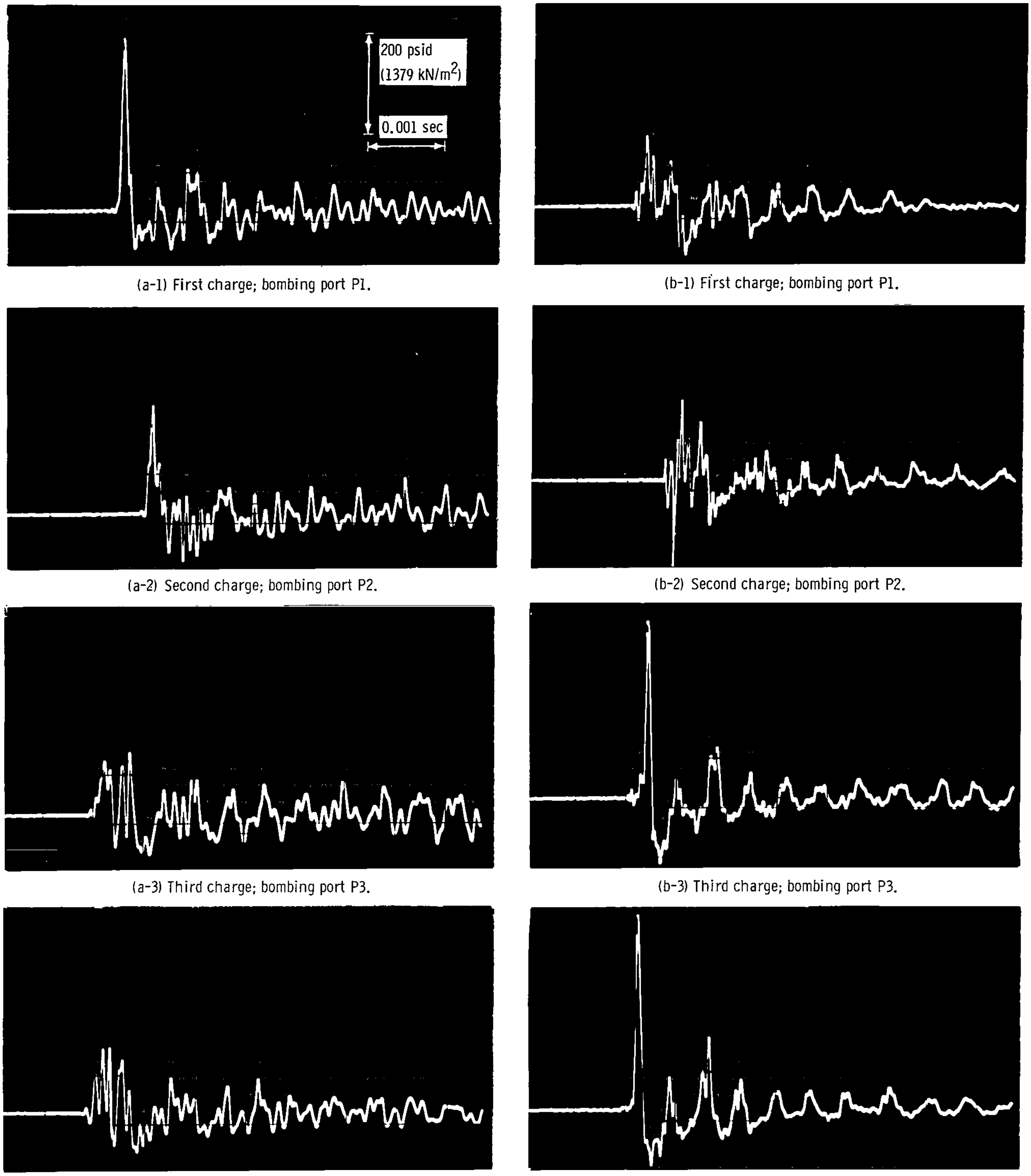
As noted earlier, modifications to the machine gun necessary to make it operate when firing into the high pressure field inside the combustor are given in the appendix. These modifications included the use of a check valve located in the gun barrel for consistent operation at chamber pressures over 125 psia (862 kN/m^2 abs). Pressure histories of perturbations observed at location T1 in a pressurized system with and without check valves are shown in figure 10. In figure 10(a) is shown a typical perturbation when no check valve was present in the gun barrel. A perturbation when check valve 1 was present is shown in figure 10(b), while a similar perturbation when valve 2 was installed is shown in figure 10(c). Both check valves 1 and 2, which are shown in a later figure, are discussed in more detail later. Since the chamber pressure was 100 psia (690 kN/m^2 abs) with no check valve and 300 psia (2070 kN/m^2 abs) with one present, a meaningful quantitative comparison between pulse amplitudes is difficult to make. It is obvious that the initial pulse is also the maximum pulse in figure 10(a), but the same is not true in figures 10(b) and (c). The amplitude and rate of growth of the initial pulse is important to the initiation of combustion instability. In view of this, no check valve in the system is considered ideal, but if a check valve must be used, then a low-mass poppet is better than a high-mass one because, as shown in figures 10(b) and (c), it allows passage of a larger initial pulse amplitude.

To provide a comparison between perturbation characteristics produced by the machine gun and those via the more conventional multiport bomb ring, several tests



(b) Transducer location T2.

Figure 11. - Duplicate test conditions.



(a-1) First charge; bombing port P1.

(a-2) Second charge; bombing port P2.

(a-3) Third charge; bombing port P3.

(a-4) Fourth charge; bombing port P4.

(a) Transducer location T2.

(b-1) First charge; bombing port P1.

(b-2) Second charge; bombing port P2.

(b-3) Third charge; bombing port P3.

(b-4) Fourth charge; bombing port P4.

(b) Transducer location T4.

Figure 12. - Typical pressure histories of successive perturbations induced tangentially by bomb ring in combustor burning storable propellant combination. Charge size, 40.9 grains (2.6503 g).

were conducted with RDX explosives induced through four tangentially oriented ports in a combustion chamber burning the storable propellant combination at 100 psia (690 kN/m^2 abs). A sketch of the bomb ring was presented in figure 3. Transducer location T2 was situated between ports P3 and P4, while T4 was situated between P1 and P2. Typical pressure perturbation histories of the same size charge induced from port P1 in two identical tests are shown in figure 11. Figure 11(a) shows the histories as observed at location T4, while figure 11(b) shows the histories as observed at location T2. A comparison of the histories at either location shows a remarkable reproducibility. On the other hand, for a constant point of observation, the variation in perturbation characteristics as the bombing port is changed is shown in figure 12. Figure 12(a) shows the histories as observed at location T2, while figure 12(b) are those observed at location T4. As one might expect, with the RDX charge sizes all the same, the amplitude characterization of a pressure perturbation is dependent on the processes—such as, chemical augmentation—which occur between the port of bombing and the point of observation. Furthermore, the injector pattern probably has some influence on how a perturbation will look at different locations in the chamber.

If different charge sizes were fired from ports P1 to P4, then a typical plot of the maximum pressure differential (peak-to-peak amplitude) as a function of charge size is shown in figure 13. It is evident that the amount of scatter present prevents a more

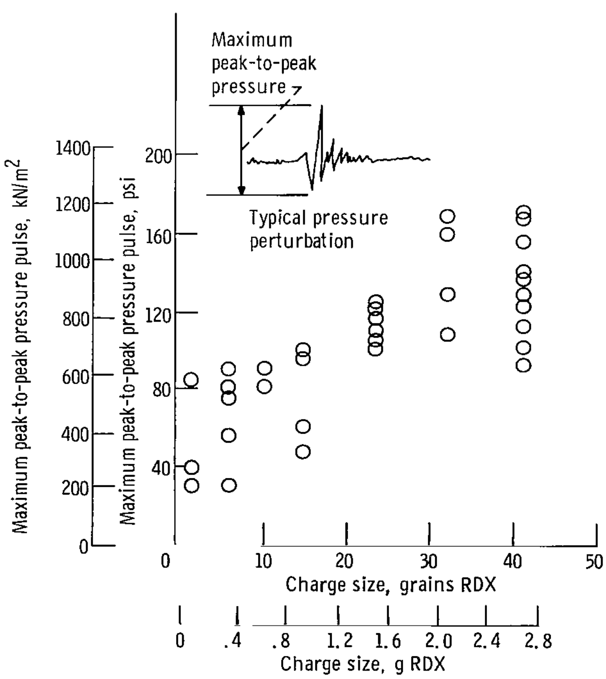


Figure 13. - Pressure perturbation pulse amplitudes produced by detonating various sized RDX charges from various ports (ref. 3). Transducer location T2.

detailed characterization of the pressure perturbations. These data and similar scatter in data from other investigators indicate serious shortcomings regarding the use of these devices (pulse guns or bomb rings) for stability rating, and in particular, when trying to distinguish relatively small effects of configuration changes. From figures 11 to 13 it may be concluded that while a pressure perturbation history seems reproducible under identical test and observation conditions, a change in either the operating conditions or point of observation to port of bombing will change the observed characteristics. In order to obtain more meaningful quantitative data of an explosively induced perturbation, the bomb port-to-transducer distance should be kept constant. Although this can be accomplished with both the bomb ring and machine gun, the bomb ring does not lend itself as readily to such operation.

Measurement of the Characteristics of an Explosively Induced Pressure Perturbation

From consideration of the characteristics of an ideal perturbation, it was felt that peak-to-peak amplitude measurements were not quite as meaningful as mean-to-peak (overpressure) measurements in analyzing the effect of a pressure perturbation on the various mechanisms of combustion. The initial pressure pulse or spike was thought to be the best measurement to make since it is an indication of the strength of the shock front. Subsequent pulses may be influenced by wave reflections. Furthermore, measurement of wave transit times between specific locations in the chamber could be made only by using the initial spike. Given the distances between such locations, the wave transit times could be used to calculate wave velocities through the combustor. Thus, the initial spike was considered a primary measurement.

Unfortunately, as noted earlier, not all measured pressure perturbations exhibited a definite initial pulse. Instead, the pressure would increase in a random manner and at a relatively slow rate until a maximum amplitude was reached (see fig. 6(b)). Then the perturbation would damp out. Since the maximum pulse occurred at a random time during the total pressure perturbation, no accurate wave transit times could be measured. However, plots of the maximum pulse amplitude against charge size correlated in a similar manner to those for the initial pulse amplitude. Consequently, whenever data exhibited no initial pulses, measurements of maximum amplitude were made. As shown in figure 6(c), sometimes both initial as well as maximum pulses would be present. In these cases, both amplitudes were measured.

The measurement of the initial pulse, maximum pulse, and wave transit time is illustrated in figure 14. Finally, the decay rate (or decay time) of a perturbation was considered a meaningful parameter but measurements of decay rate were not made because of problems in properly filtering the signals.

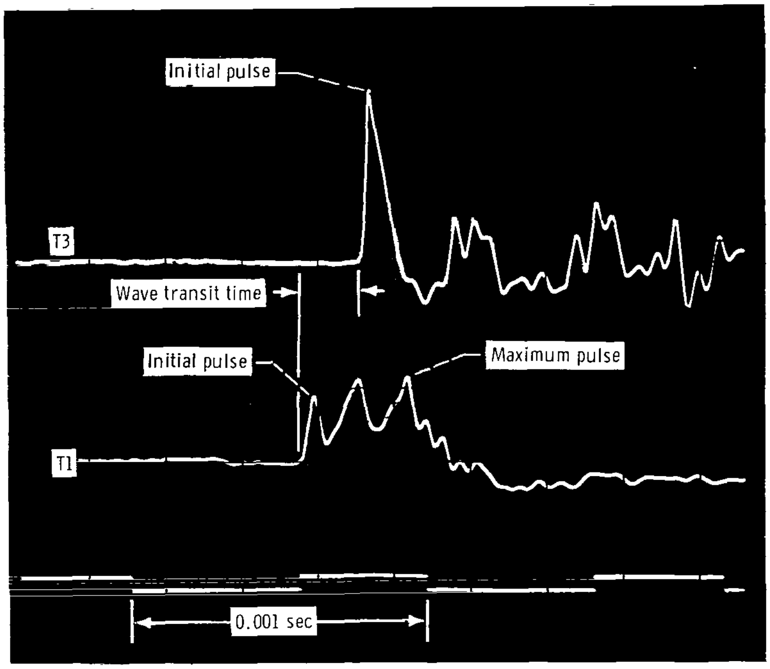


Figure 14. - Measured characteristics of pressure perturbation history as observed at transducer locations T1 and T3.

PERTURBATION ANALYSIS

The material presented up to this point has served to characterize qualitatively explosively induced pressure perturbations within a rocket combustion chamber. Material presented hereafter will be more quantitative in nature. Test results from the evaluation of the machine gun are grouped into two categories; the first are those tests conducted at 100 psia (690 kN/m^2 abs) with the tangential port, and second, those tests conducted at 300 psia (2070 kN/m^2 abs) with the radial port. In each category, results from the helium tests are presented initially followed by the combustion test results. Finally, a comparison is made between test results using the machine gun and bomb rating devices.

Experiments at a Chamber Pressure of 100 psia (690 kN/m^2 abs) with the Tangential Port

Experiments were conducted with the machine gun tangentially mounted to a capped combustion chamber which was pressurized to 100 psia (690 kN/m^2 abs) with helium

gas. In one test, a series of six charges—ranging from 24.5 to 39.0 grains (1.587 to 2.527 g)—were fired consecutively. Resultant maximum pulse amplitudes of the pressure perturbations as observed at four chamber locations plotted against charge size are shown in figure 15. It is evident from this figure that the pulse amplitudes decrease from location T1 to T3. (Note again that T1 amplitudes are uncorrected.) From consideration of possible shock front patterns which the front may exhibit as it propagates away from the point of entry into the combustion chamber, two possible propagation patterns were envisioned. Because of the tangential placement of the injection port, a rotating-like wave seemed possible. On the other hand, from results presented in references 5 and 17, the shock front may propagate in a hemispherical manner away from the point of entry. By noting how the perturbation amplitude varied from one transducer location to another and the wave transit times between these locations, it became evident that the shock front propagated in an approximately hemispherical manner from the point of entry

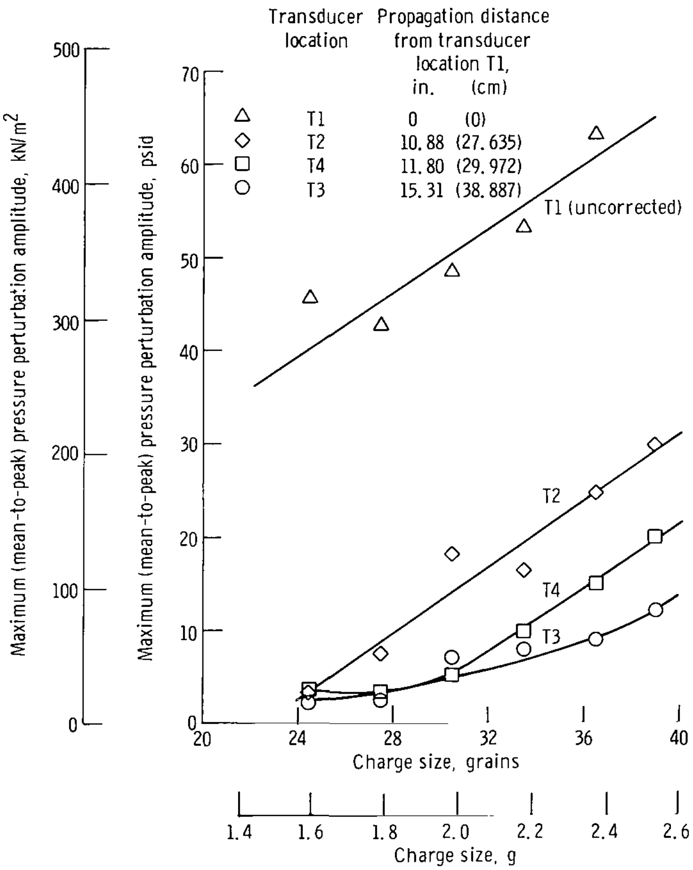
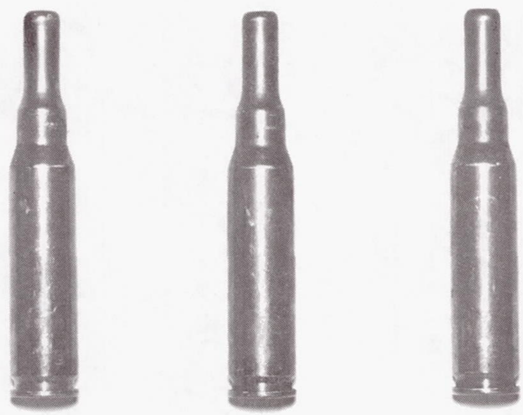


Figure 15. - Maximum pressure perturbation amplitude as function of charge size for machine gun rating device fired tangentially into capped combustion chamber pressurized to 100 psia (690 kN/m^2 abs) with helium.

to the opposite chamber wall. If in figure 4 the distances denoted by s are called the propagation distances (since they form the radii of several size hemispheres), then it becomes evident that the perturbation amplitudes of the data presented in figure 15 decrease with increasing propagation distance. Because of the inert medium through which these perturbations propagated, this pressure amplitude decay as a function of distance agrees with acoustic theory. Tests were also conducted with inert gases other than helium but are not reported because of (1) a different chamber pressure or (2) different speed of sound as compared with the reported combustion tests. These unreported tests could have been compared by using nondimensional analysis and probably would have yielded useful information. Such an approach was not pursued, however, because of the time involved and the primary interest in results from combustion tests. Since some of these tests exhibited initial pulses and thus permitted measurement of wave transit times, a select number of transit times were plotted as a function of charge size. Results showed that the wave transit times between T2 and T4—which had very



(a) Typical cartridges following explosion of 21.5 grains (1.393 g) nitrocellulose.

(b) Typical cartridges following explosion of 39.0 grains (2.527 g) nitrocellulose.

Figure 16. - Typical spent cartridges.

similar propagation distances s—were smaller than those between T2 and T3. It was concluded that such results further strengthened the model of an approximately hemispherical pattern of propagation.

Further consideration of figure 15 shows the pulse amplitudes to increase with charge size. In many of the unreported tests, the two largest charge sizes did not necessarily produce the largest amplitudes. This may be explained by examining the spent cartridges at both the small and large charge sizes. Shown in figure 16(a) are three typical spent cartridges which were loaded with 21.5 grains (1.393 g), while figure 16(b) shows three similar cartridges which contained 39.0 grains (2.527 g). The

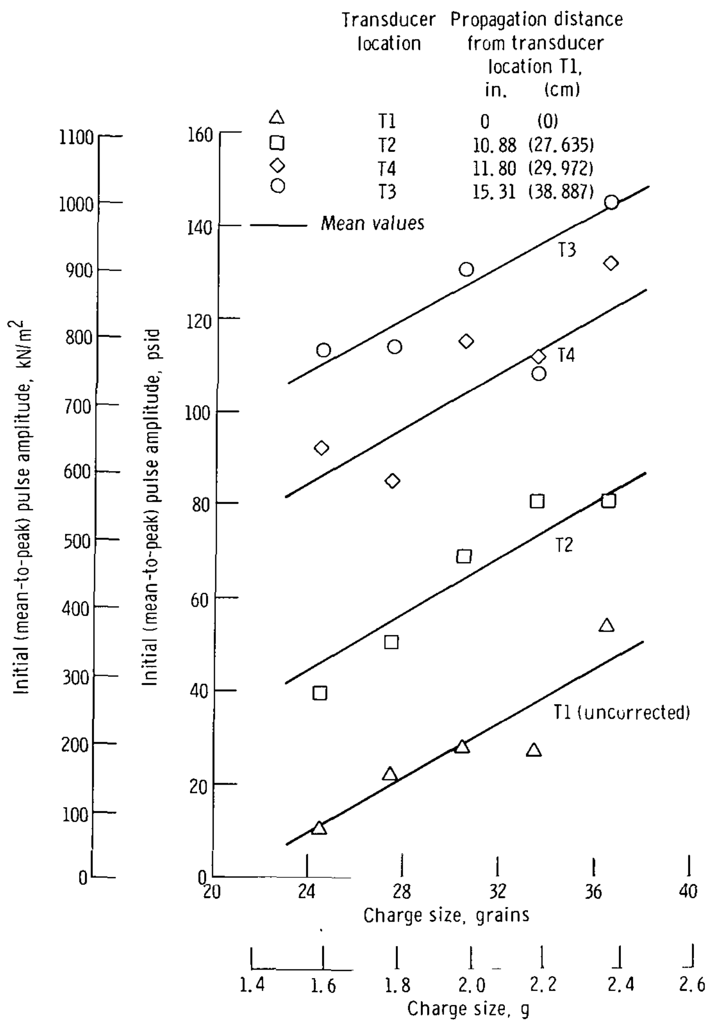


Figure 17. - Initial pulse amplitude as function of charge size for machine gun rating device fired tangentially into combustor burning storable propellant combination at 100 psia (690 kN/m^2 abs). Oxidant-fuel ratio O/F = 2.06.

amount of cartridge deformation present in the largest charge size is probably due to overpacking of the cartridges. The amount of explosive energy lost, which is associated with deformation of a cartridge, apparently results in a decrease in perturbation energy and, consequently, lower pressure perturbation amplitudes. This limitation to the machine gun as a rating device possibly may be alleviated by (1) stronger cartridges or (2) use of a larger machine gun—perhaps a 50-caliber gun.

Results of combustion tests using an earth-storable propellant combination (N_2O_4/ 50 percent UDMH-50 percent N_2H_4) are presented next For each run in this series of tests, up to eight increasingly larger charge sizes were fired while maintaining all other operating parameters essentially constant. Figure 17 presents the resultant initial pulse pressure perturbation amplitudes as observed at four different locations in the chamber plotted against charge size for a typical combustor operating at an O/F of 2.06. In this figure, the lines through the data reflect the mean values of the initial pulse amplitudes. Although seven charges were fired in this test, only the last five could be detected as perturbations in the chamber pressure. A strong possible reason why small charge sizes could not be detected is the damping effect of the combustion medium. It seems that a threshold exists below which any type of perturbation is damped and above which perturbations may grow because of chemical augmentation (see refs. 2 and 6). Furthermore, in some unreported tests, which were conducted at NASA Lewis and by the aerospace industry, relatively large charges were fired into a given combustor configuration operating at a given condition and initiated combustion instability, while the same size charges fired into a different combustor configuration and/or operating at a different condition were apparently absorbed by the combustion medium and had no discernible pressure perturbations. This somewhat sketchy evidence that the threshold is a function of geometry and/or operating condition may explain why, in some tests, a large charge resulted in a relatively small perturbation or could not be detected at all.

Because the data presented in figure 17 were for initial pulse amplitudes, measurement of wave transit times between transducer locations was possible. Results are presented in figure 18. As shown, wave transit times decrease with increasingly larger charge sizes. With the same type of argument used for the inert gas tests and noting the trend of wave transit times as shown in figure 18, it was again concluded that the shock front propagated away from the point of entry in an approximately hemispherical manner.

From figures 17 and 18, it is apparent that, as the size of an explosive charge is increased, the resultant perturbation in pressure shows an increasing initial pulse amplitude as well as an increasing wave velocity. If this wave is traversing a combustion chamber in such a direction as to interact with the injected propellants, then the effect of the steep-fronted wave is to increase jet or droplet breakup. This results in more energy being added to the wave—thus increasing its amplitude (refs. 10, 15, and 16).

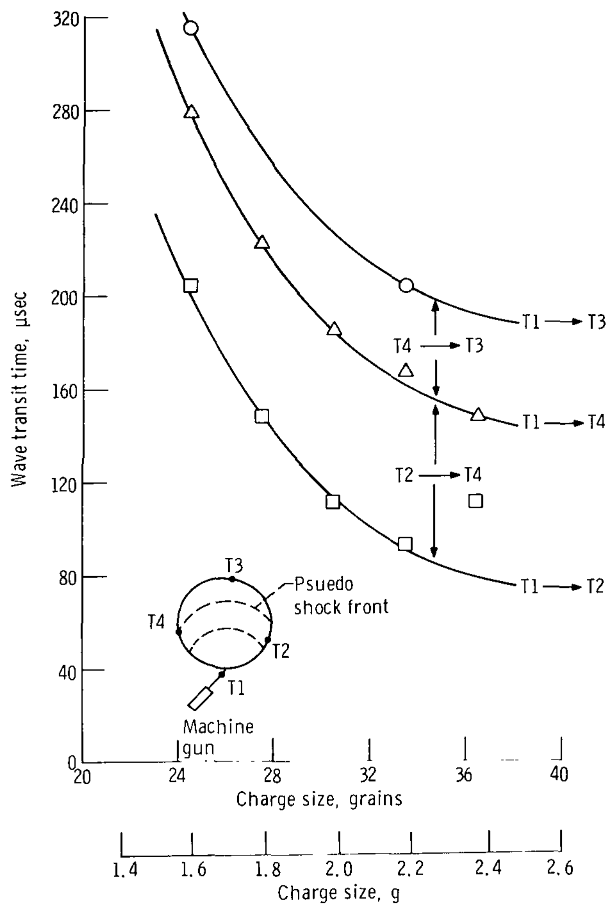


Figure 18. - Wave transit time as function of charge size for machine gun rating device fired tangentially into combustor burning storable propellant combination at 100 psia (690 kN/m^2 abs). Nominal oxidant-fuel ratio O/F = 2.06.

Imagine a finite size volume within the combustion chamber through which the propellants and products of combustion flow. The effect of a sudden pressure change on any given cross-sectional area of this volume (e.g., a detonation front traversing this volume) would result in a shearing action and consequent increase breakup of the propellants. For a given relative flow rate of propellants, the effect of increasing the velocity of this front is to cause increased breakup per given volume. At some critical condition, the amount of increased breakup per given volume may be such as to initiate instability. Thus, not only is the perturbation amplitude important in initiating combustion instability, but its velocity of propagation may likewise be important.

To provide further understanding on this postulation, a series of tests with the storable propellant combination were conducted with the bomb ring positioned at several axial locations in a given combustor configuration. Results from these tests are pre-

sented in figure 19. In this figure, the charge size which initiated instability is plotted as a function of axial distance from the injector face for two different mixture ratios. The most important observations to be noted from figure 19 are the following:

(1) The most sensitive zone to any perturbation extends from the injector face to about 8 inches (20.32 cm) from the injector. As the bomb ring is moved beyond this point, increasingly larger charge sizes are needed to initiate instability. Large charge sizes are necessary probably because the amount of unburned propellants per unit volume decrease radically with distance from the injector face. Although this result is true for the data presented in figure 19, other studies (ref. 18) have noted conflicting evidence.

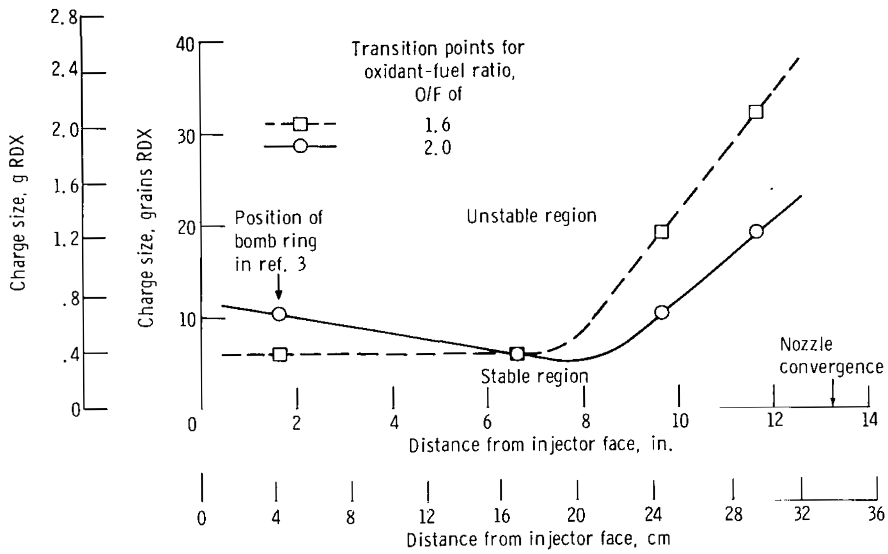


Figure 19. - Effect of bomb ring axial position on minimum charge size for instability.

(2) With the bomb ring positioned nearest to the injector, increasing the O/F resulted in a larger charge size to initiate instability (see also ref. 3). Larger charge sizes are necessary probably because of a change in propellant breakup characteristics which results from a relative flow rate change between propellants when the O/F is changed.

Further insight into the characteristics of a pressure perturbation as it traverses the combustion chamber (assuming hemispherical propagation) may be gained if some of the previously presented data from the machine gun tests—in particular, figures 17 and 18—are plotted as a function of propagation distance (see fig. 4). In figure 20 is presented the initial pulse amplitude for three charge sizes plotted against propagation distance s for a hemispherical pattern of propagation. The amplitudes shown are those which fall along the mean lines presented in figure 17. It is evident that, as the shock

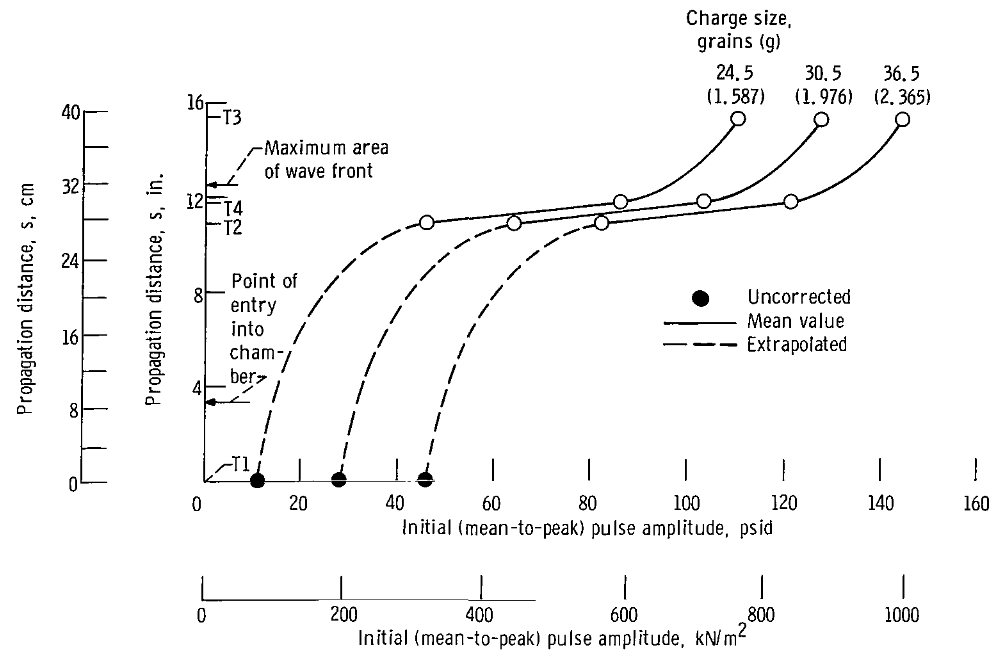


Figure 20. - Propagation distance versus initial pulse amplitude for three charge sizes fired tangentially into combustor burning storable propellant combination at 100 psia (690 kN/m^2 abs). Oxidant-fuel ratio O/F = 2.06. Machine gun rating device.

front travels through the combustion chamber, its amplitude increases appreciably. This is probably because of the effect of chemical augmentation (refs. 2 and 16) of this particular propellant combination. Furthermore, the shock front amplitude has the greatest rate of growth at about 8 inches (20.32 cm) from the point of entry into the chamber. With the approximately hemispherical pattern of propagation, the frontal area, and hence chemical augmentation, is greatest near this value of s.

In figure 21 are presented the wave transit times for the same data points shown in figure 20 plotted against propagation distance s for a hemispherical pattern of propagation. As shown, the slope at any given point along any one of the curves for a constant charge size gives the instantaneous velocity of the wave front at that point. It becomes evident that the front decelerates as it nears the region of maximum frontal area and then accelerates to the opposite wall. The average sonic velocity of the combustion gases at the given operating condition (based on the simple expression $\sqrt{gkRT}$) is 3765 feet per second (1147.6 m/sec). Calculations of the Mach number along any one of the curves of constant charge size show that the wave is supersonic in the initially perturbed volume as well as at the side opposite the point of entry and subsonic in the region where the detonation-like wave has the maximum frontal area. According to detonation theory, however, a detonation wave of constant frontal area must increase in velocity as its amplitude increases, and at the condition of equilibrium, both the velocity

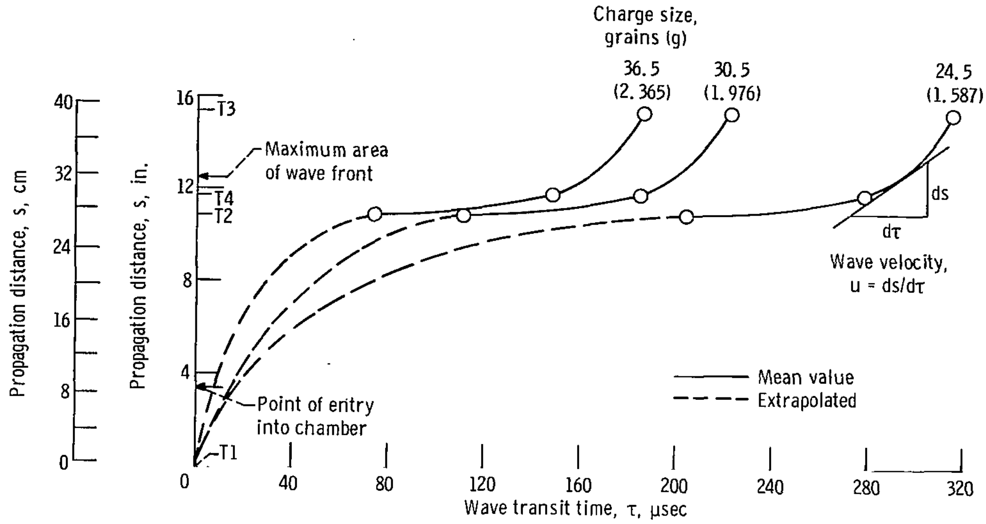


Figure 21. - Propagation distance versus wave transit time for three charge sizes induced in combustor burning storable propellant combination. Tangential port; sonic velocity, 3765 feet per second (1147.6 m/sec).

and amplitude will remain constant. Thus, there seems to be a discrepancy between the experimental results and the theory. Two possible explanations for this discrepancy are as follows: First, if the propagation pattern was not truly hemispherical, then the corrected propagation distance could show a different velocity characteristics for a perturbation traversing a combustion chamber. Second, since the propagating detonation-like wave amplitude did not reach a constant value, the condition of equilibrium was not attained, and consequently, the analysis that has been made is not truly applicable. The influence of a changing frontal area on a nonequilibrium detonation wave is unknown. Further research with more pressure transducers located on the chamber wall and in the flow field would shed more light in this area.

Experiments at a Chamber Pressure of 300 psia (2070 kN/m^2 abs) with the Radial Port

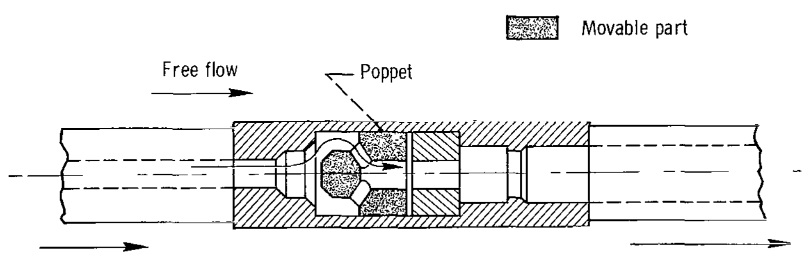
In previous tests with the machine gun, where the tangential port was used, the transverse mode of instability was initiated most often. This was the case even though the test results indicated an approximately hemispherical shock front growth from the end of the gun barrel. The wave transit time between locations T2 and T4 is comparatively small as shown in figure 18. Because of this and the pattern of growth, it would seem reasonable to expect symmetry in the perturbation characteristics as observed at

T2 and T4. However, figures 9(b) and (c) show the amplitude characteristics to be different. For example, at location T4 the initial pulse has the maximum amplitude, but this is not the case at T2. Possible explanations for this are (1) the gun was oriented towards location T2 and (2) the pattern of injector jets (ref. 19). Again, further research with a combustor having more transducers would shed more light in this area.

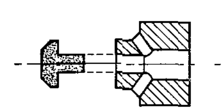
We thought that if a more symmetrical perturbation were induced, the analysis of the characteristics would become somewhat easier. Accordingly, the gun barrel was mounted in a radial port position (see fig. 1). Also, the range of chamber pressure levels over which the gun would operate was considered quite important in evaluating the gun. Chamber pressure level was raised to 300 psia (2070 kN/m^2 abs), a change which should have no effect on the pattern of growth (ref. 5).

With the gun mounted radially to a capped combustion chamber which was pressurized with helium, it was found that jamming of the cartridges in the breech occurred repeatedly at back pressures over 125 psia (862 kN/m^2 abs). To permit operation of the gun at back pressures at least up to 300 psia (2070 kN/m^2 abs), several modified check valve designs were tested. The following discussion will show results obtained with two such valves in the system.

The first valve design, with a poppet weight of 43.4 grams, was designated check valve 1 and is shown in figure 22(a). The second valve design, having a poppet weight of 12.5 grams, was designated check valve 2 and is shown in figure 22(b). In figure 23 are presented resultant pressure perturbation amplitudes as observed at transducer location T1 plotted against charge size. Both first spike and maximum amplitudes are shown (also see fig. 10). As can be seen, the amplitudes increase linearly with increasing charge size. Although pressure perturbations which passed through check valve 2



(a) Check valve 1; poppet weight, 43.4 grams.


(b) Check valve 2; poppet weight, 12.5 grams.

CD-10175-33

Figure 22.- Check valve designs.

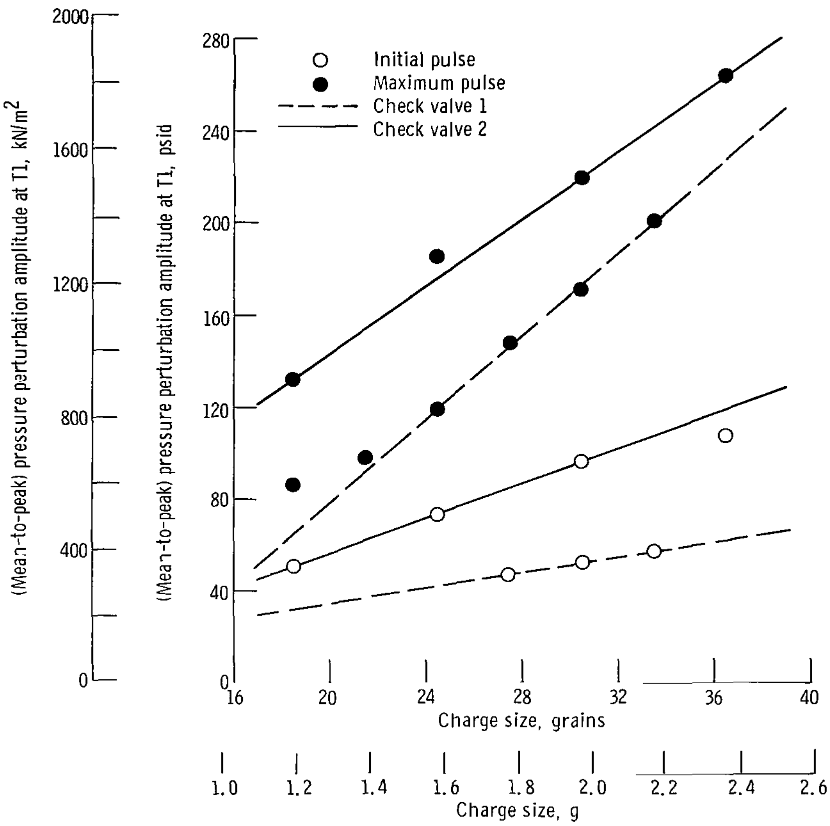


Figure 23. - Pressure perturbation amplitude at transducer location T1 as function of charge size for machine gun rating device with check valves 1 and 2. Helium gas at 300-psia (2070-kN/m^2 abs) environment and radial port injection.

had larger amplitudes, of more importance is the fact that valve 2 also passed initial spikes more readily. For example, at a charge size of 30.5 grains (1.976 g), the maximum-to-first spike amplitude ratio was about 3.3 with valve 1 and 2.3 with valve 2. Furthermore, as shown in figure 24, pressure rise rates of the initial spikes increase linearly with increasing charge size. Ideally, a very fast rise rate would be expected with no check valve. Thus check valve 2 is a step in the right direction since initial spikes passing through it have a rise rate of approximately 3.65 times greater than valve 1 (compared to a mass ratio of 3.47) at a charge size of 30.5 grains (1.976 g). Finally, maximum pulse amplitudes of pressure perturbations as observed in the chamber at transducer location T2 for check valves 1 and 2 are presented in figure 25. Amplitudes with valve 2 are much larger than with valve 1.

The tests used to evaluate the two check valve designs proved that a modified machine gun could be operated with back pressures up to at least 300 psia (2070 kN/m^2 abs). Thus, for the final step in the machine gun evaluation study, the gun—fitted with check

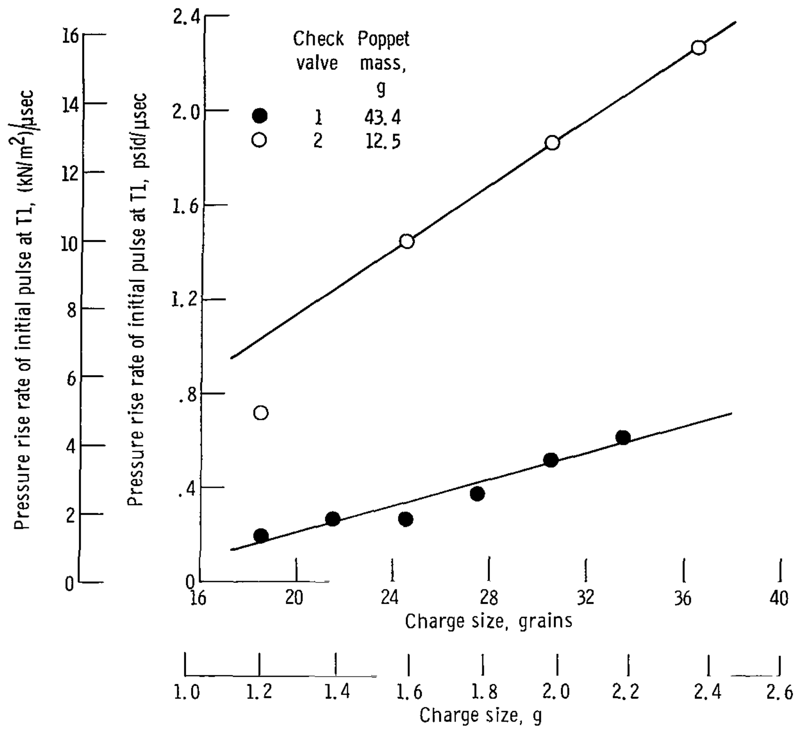


Figure 24. - Pressure rise rate of initial pulse at transducer location T1 as function of charge size for machine gun rating device with two types of check valves. Helium gas at 300-psia (2070-kN/m^2 abs) environment and radial port injection.

valve 2—was mounted radially to a combustor burning a hydrogen-oxygen propellant combination at 300 psia (2070 kN/m^2 abs). For each run in this series, up to six constant size charges were fired, while the HIT was ramped downward. In these tests, the O/F was held essentially constant during a single run, but slight changes in O/F occurred between runs.

In earlier unreported stability tests using the multiport bomb ring along with the hydrogen injection temperature ramping technique in an H-O combustor, a very strong perturbation damping effect was noted by increasing the HIT margin. It should be recalled from previous discussion that since the HIT margin is the temperature increment above the boundary of transition to instability, a HIT margin of zero corresponds to the point where combustion instability is triggered spontaneously. Increasing the margin results in greater stability. Although the transition temperature varies according to the combustor configuration, for these tests it was about 121° R (67.2 K). This series of machine gun tests was designed to obtain more meaningful data for further analysis of the relation between the explosive and temperature ramping rating techniques. Before investigating this relation, however, the recognized possibility of

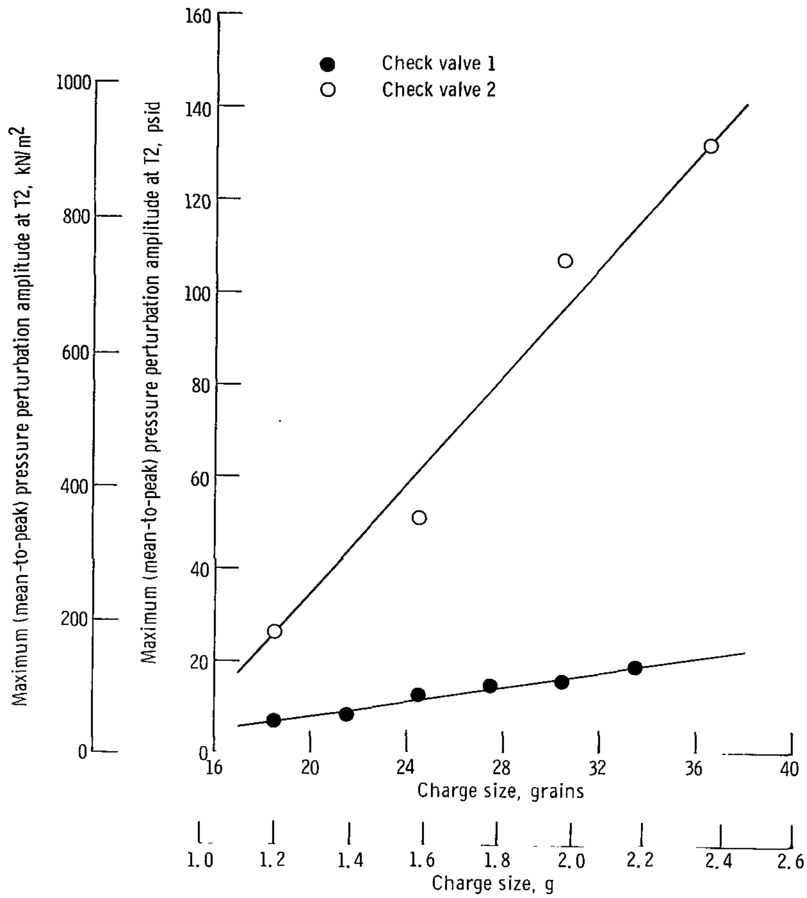


Figure 25. - Maximum pressure perturbation amplitude at transducer location T2 as function of charge size for machine gun rating device tested with check valves 1 and 2. Capped combustion chamber pressurized to 300 psia (2070 kN/m^2 abs) with helium. Radial port injection.

the stabilizing influence of adding a gun barrel cavity to a rocket combustor (ref. 5) was studied. A comparison was made between tests conducted under identical operating conditions but with and without the barrel cavity. In reference 1, test 673 (table II) was conducted with no machine gun, with the same combustor configuration, and under practically identical operating conditions as tests conducted in this series. In the referenced test, the HIT at transition into instability was 125° R (69.4 K). By comparison, the HIT at transition in the tests reported herein was 121° R (67.2 K). Since this difference in transition temperature is not significant, it can be concluded that mounting the machine gun to the combustor configuration produced no change in the stability limits under the conditions of these tests.

Figure 26 presents the resultant maximum pressure perturbation amplitudes as observed at location T1 plotted against charge size. An appreciable amount of scatter is present. Figure 27 presents several of the aforementioned amplitudes increased as HIT margin decreased, and decreasing the O/F resulted in lower amplitude perturbations.

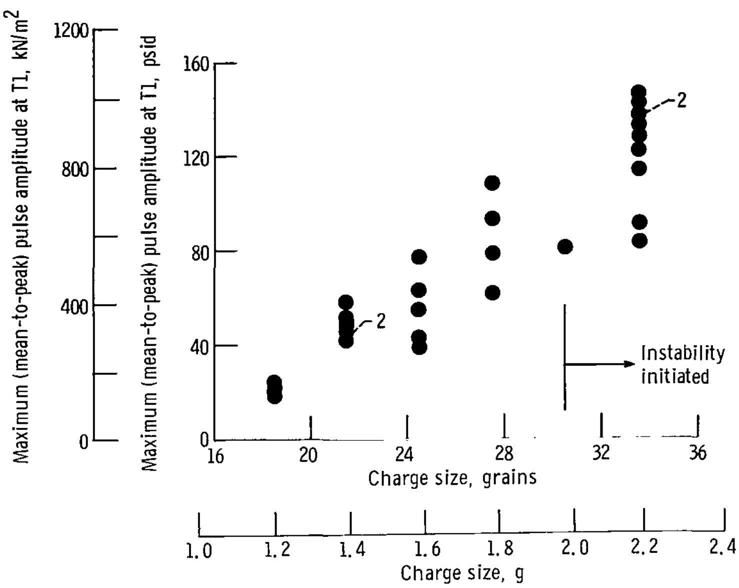


Figure 26. - Maximum pulse amplitude at transducer location T1 as function of charge size for machine gun rating device fired radially into combustor burning hydrogen-oxygen propellant combination at 312 psia (2151 kN/m^2 abs). Check valve 2. Hydrogen injection temperature and oxidant-fuel ratio O/F varied.

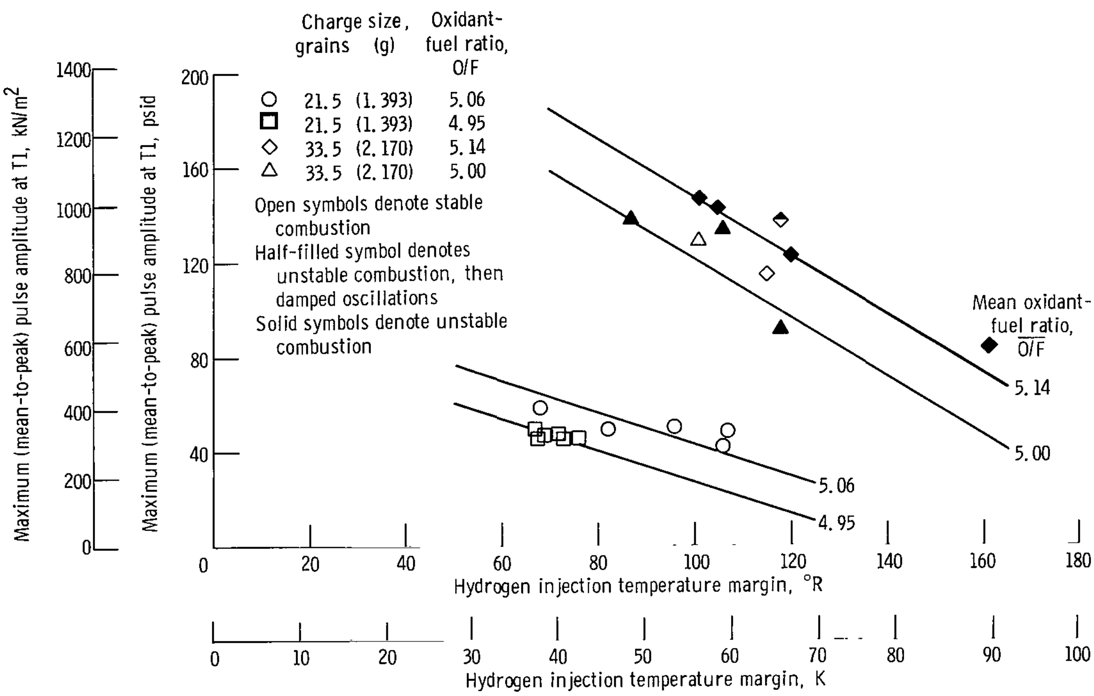


Figure 27. - Maximum pulse amplitude at transducer location T1 as function of hydrogen injection temperature margin for two charge sizes and various oxidant-fuel ratios at 312 psia (2151 kN/m^2 abs). Machine gun rating device with check valve 2 and radial port injection.

Thus, the "scatter" shown in figure 26 is principally due to HIT and O/F variations and not measurement inaccuracies or poor quality control on the explosive cartridges. It should be pointed out that the section of the gun barrel between the breech and check valve may contain a certain amount of combustion gases which are trapped between firings. This may have some effect on the infinite probe (T1) response during the succeeding charge firing, but the effect is considered very small.

Results similar to those just presented were noted at transducer locations T2 and T4, although the amplitudes at these positions were lower than at T1. It seems that perturbation amplitudes decreased with increasing distance traveled in the chamber. Although the opposite effect was noted for the storable propellant combinations, it should be noted that the check valve did not allow a steep-fronted perturbation into the combustion chamber as seen with the storable tests with no check valve. This could account very well for amplitude losses instead of gains.

We may conclude that exploding a large charge at a high HIT margin produces only a small amplitude pressure perturbation. Repeating this at a lower margin will result in a much larger amplitude and, quite possibly, will initiate combustion instability. Furthermore, no differences could be detected in perturbation propagation patterns between the tangential and radial injection ports.

Comparison of Results from the Machine Gun and Bomb Ring Rating Devices

To provide a comparison of results from different explosive-type rating devices, a typical combustor was stability rated using first a bomb ring (RDX) followed by the machine gun (nitrocellulose). Figure 28 presents **the results** of both series of tests in

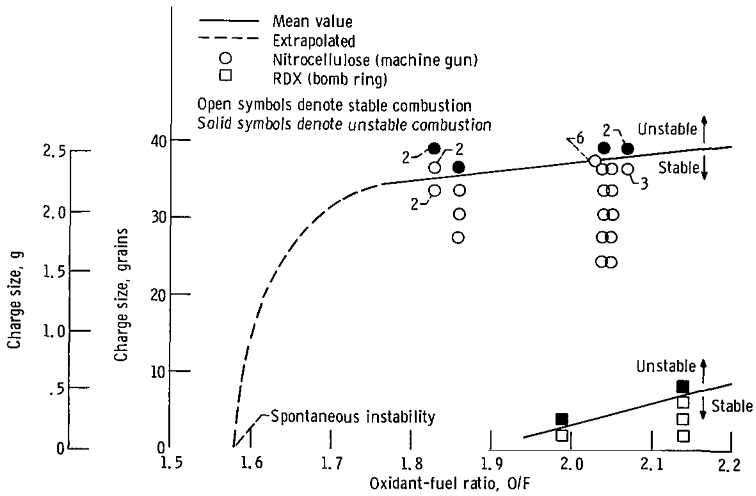


Figure 28. - Charge size versus oxidant-fuel ratio O/F for combustor burning storable propellant combination at 100 psia (690 kN/m^2 abs). Comparison of results from machine gun and bomb ring rating devices.

which the storable propellant combinations was burned at 100-psia (690-kN/m^2 abs) chamber pressure. As shown, about 33 grains (2.170 g) more nitrocellulose than RDX were required to induce instability for the configuration tested. Results are shown in terms of charge size only because this is conventional in the industry More fundamental attempts to correlate in terms of brisance and energy showed only a slight degree of correlation. A more meaningful relation is shown, however, in figure 29 where inspection reveals that the initial spikes of the perturbations that induced instability have about the same amplitudes. The scatter present with the RDX pulses is probably due to the bomb-to-transducer port relative positions as already discussed.

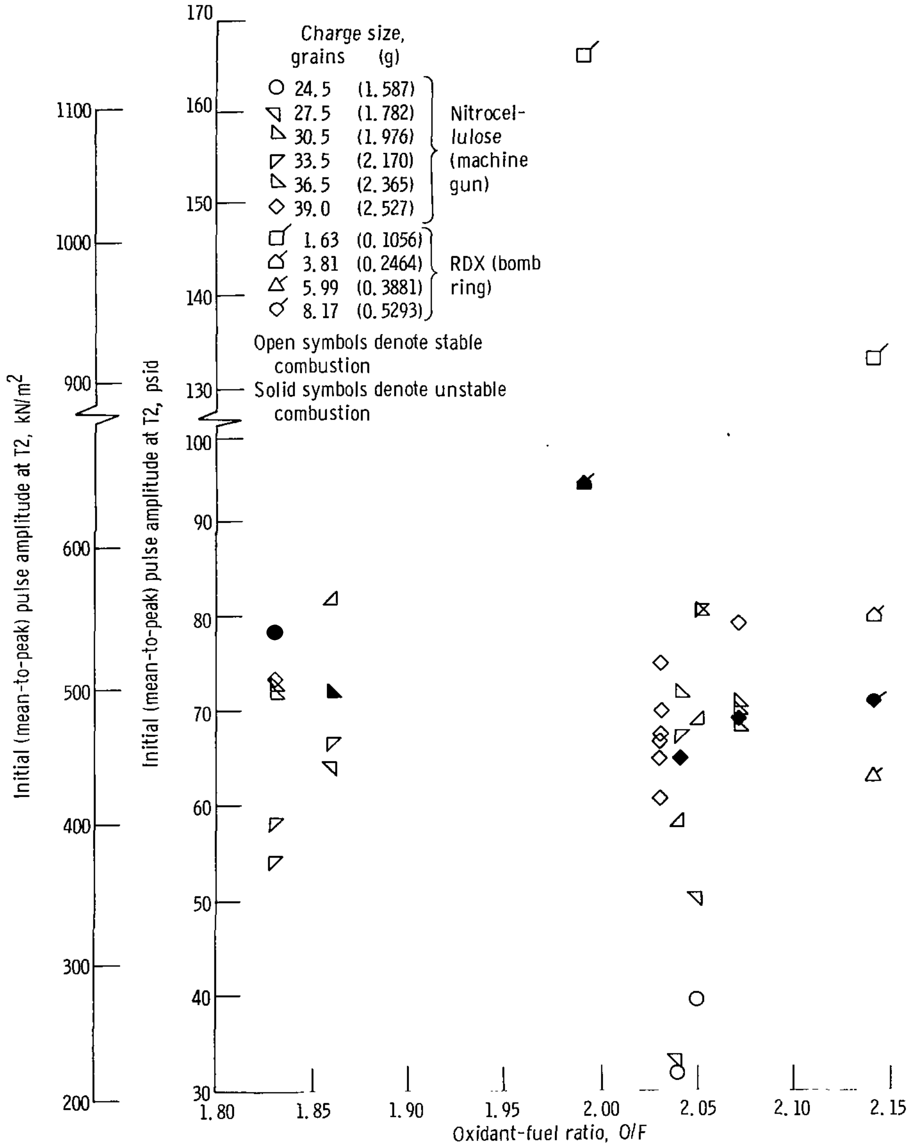


Figure 29. - Initial pulse amplitude at transducer location T2 versus oxidant-fuel ratio O/F for several charge sizes of nitrocellulose and RDX.

The previously discussed results from the machine gun evaluation tests showed that the machine gun can initiate combustion instability over a wide range of operating conditions. Although the multiport bomb ring is a proven stability rating device, the machine gun has several advantages. First, because only one chamber injection port is used, the machine gun appears more adaptable to flight-type rocket engines and would have less likelihood of damping because of the smaller number of acoustic cavities. Second, meaningful information can be recorded more easily with regard to the interaction of the injector geometry and an explosively induced perturbation. Third, since many finely graduated charges could be preprogrammed before a series of tests, the determination of a stability boundary may be made more precisely and economically.

Although the machine gun offers the aforementioned advantages over the bomb ring, several limitations exist at the present crude state of development. Overpacking problems with the largest charge sizes resulted in lower maximum pressure perturbation amplitudes. This problem could possibly be eliminated by using a larger size machine gun—such as a 50-caliber. Another problem is operation of the machine gun at high chamber pressures. Although the modified check valve designs previously discussed worked, the initial pulse amplitude and rate of pressure rise of a perturbation were somewhat attenuated. Other valve arrangements could be made to perform with much less attenuation. The use of both a 50-caliber machine gun and a different type of check valve are planned for future evaluation.

SUMMARY OF RESULTS

A summary of the results of a study to find a new explosive device for stability rating of rocket combustors is as follows:

1. Using a 30-caliber machine gun to perturb a combustion environment worked successfully with earth storable as well as hydrogen-oxygen propellant combinations. The explosively induced perturbations initiated acoustic mode combustion instability in many combustors operating at thrusts up to 20 000 pounds (89 kN).

2. The gun, with only slight modifications to the bolt actuating mechanism, fired into environments pressurized up to 125 psia (862 kN/m^2 abs). The addition of a modified check valve in the barrel permitted further tests to be made at back (chamber) pressures up to 300 psia (2070 kN/m^2 abs).

3. Initial and maximum pulse amplitudes of pressure perturbations as well as wave transit times using the machine gun were very reproducible. Perturbation characteristics could be related to operating conditions of the gun and combustor.

4. Increasing the size of a charge resulted in increased pulse amplitudes and wave velocities through the combustion chamber. Overpacking problems with the largest

5. With the storable propellant combination, wave amplitude growth was measured and related to distance traveled in the chamber.

6. With the hydrogen-oxygen propellant combination, lower hydrogen injection temperature margins yielded larger perturbation amplitudes for a given charge size.

7. The effects of tangential against radial port injection could not be established from these data.

8. Inducing a perturbation through a single port as compared to the multiport bomb ring enhanced the ability to interpret the measured perturbation characteristics as related to the operating conditions of the machine gun and combustor.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 27, 1968,
128-31-06-05-22.

APPENDIX - MACHINE GUN MODIFICATIONS

A typical firing cycle of the standard 30-caliber machine gun is as follows: A bolt is released either electrically (via a solenoid) or manually to close under a force exerted by a compressed spring as shown in figure 30(a). During this closing motion, the bolt engages an explosive cartridge from a link belt and inserts it in the breech. When the bolt becomes fully closed, a firing pin located in the bolt is released and discharges the explosive cartridge. Gaseous products of the resultant explosion travel down and out the gun barrel. Part of the gases, however, enters a cylinder through a small orifice (A) located in the side of the barrel and pushes a piston along the cylinder. This piston action then opens the bolt, rejecting the spent cartridge, and compressing the spring. Maximum extension of the piston, which returns the bolt to the original position, enables the pressurizing gases to be released through another orifice (B). Thus the cycle repeats.

Although successful operation of the gun is attained at atmospheric pressure, problems arise when a back pressure is placed at the end of the barrel. This back pressure, resulting from attaching the gun to a high-pressure combustor, acts on the piston continuously and prevents repetitive action of the gun. In fact, at 100-psia (690-kN/

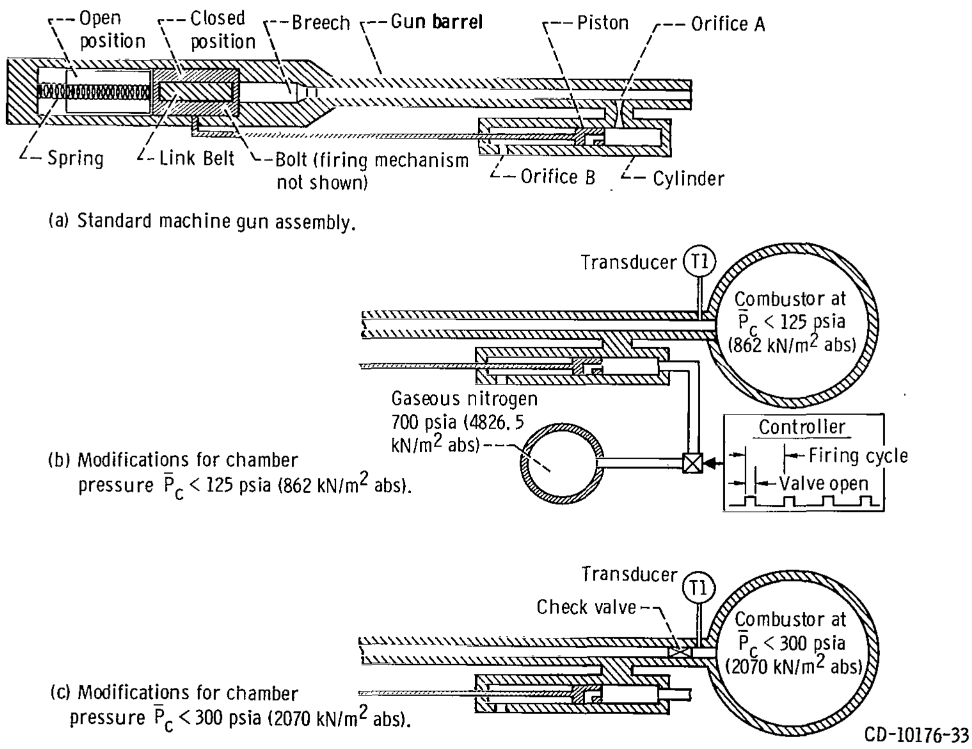


Figure 30. - Standard machine gun assembly and modifications necessary for conversion to rating device.

m^2 abs) chamber pressure, the hot combustion gases entered the barrel and exited through orifice B, resulting in overheating the cylinder and subsequent damage to the gun.

To control this back pressure action on the piston, another orifice was mounted near the muzzle end. In this manner, part of the explosion gases would operate the piston. The lower charge sizes, which produced small pressure amplitudes, necessitated using a small orifice to build up enough barrel pressure and move the piston. At large charge sizes, however, the high-pressure amplitudes overpressurized the barrel and blew out the orifice.

The best solution to the problem was to remove the orifice in the barrel and seal orifice A. A nitrogen gas supply at 700 psi (4826.5 kN/m^2 abs) was attached to the cylinder through an electrically operated valve as shown in figure 30(b). By controlling the opening and closing of the valve by an electrical controller, the overpressurization problems were solved, while at the same time an exact control was maintained over the firing rate. The controller was no more than a square wave generator having a duty cycle equal to the time interval between firings and a constant 40-millisecond pulse to open the valve. With the valve open, nitrogen gas flows to the piston and opens the bolt. Under the given conditions, 40 milliseconds was the time needed to open the bolt in this fashion. After the 40-millisecond pulse, the valve closes and residual gases in the cylinder escape through orifice B. A slight leakage around the piston allowed the bolt to close fully. The spring then returns the bolt and piston to the closed position during the remainder of the duty cycle.

The aforementioned arrangement worked well at back pressures up to 125 psia (862 kN/m^2 abs). At pressures over this value, jamming of the cartridges in the breech occurred repeatedly. This jamming was attributed to the high back pressure which resulted in a high velocity jet acting on the face of the cartridge as it was moving into the barrel. Also, heat transfer damage results because of high velocity combustion gases through the breech. A standard check valve was then placed at the muzzle end to limit this back pressure (fig. 30(c)). However, an excessive amount of the explosive energy was used in moving the valve poppet. As a consequence, only very small pressure perturbations actually entered the combustor. To decrease the work being done by the explosive in moving this poppet, another poppet was used which had about one-fourth the mass of the standard one. Satisfactory operation of the gun at pressures up to 300 psia (2070 kN/m^2 abs) was then attained.

REFERENCES

1. Wanhainen, John P.; Parish, Harold C.; and Conrad, E. William: Effect of Propellant Injection Velocity on Screech in a 20,000-Pound Hydrogen-Oxygen Rocket Engine. NASA TN D-3373, 1966.
2. Tabata, William K.; Antl, Robert J.; and Vincent, David W.: Storable Propellant Combustion Instability Program at Lewis Research Center. Paper presented at the AIAA Second Propulsion Joint Specialist Conference, Colorado Springs, Colo., June 13-17, 1966.
3. Vincent, David W.; Sokolowski, Daniel E.; and Bloomer, Harry E.: Screech Suppression Techniques for Rocket Combustors Using Earth-Storable Propellants. NASA TM X-1595, 1968.
4. Combs, L. P.; Hoehn, F. W.; and Webb, S. R.: Combustion Stability Rating Techniques. Rep. 6355-4, Rocketdyne Div., North American Aviation (AFRPL-TR-66-229, DDC No. AD-801897), Sept. 1966.
5. Combs, L. P.; Schumacher, P. E.; Kesselring, R. C.; and Kuluva, N. M.: Improvement of Bombs and Pulse Guns as Combustion Stability Rating Devices. Rep. R-7421, Rocketdyne Div., North American Aviation (AFRPL-TR-68-18, DDC No. AD-834721), Mar. 1968.
6. Peoples, R. G.; and Baker, P. D.: Stability Rating Techniques. Paper 64-11, Western States Section, Combustion Inst., Apr. 1964.
7. Thomas, John P.; and Layton, J. P.: Transient Pressure Measuring Methods Research. Rep. AMS-595t, Princeton Univ. (NASA CR-83584), Mar. 31, 1967.
8. Clayton, R. M.; and Rogero, R. S.: Experimental Measurements on a Rotating Detonation-like Wave Observed During Liquid Rocket Resonant Combustion. Tech. Rep. 32-788, Jet Propulsion Lab., California Inst. Tech. (NASA CR-67259), Aug. 15, 1965.
9. Anon.: Selection of Instrumentation for Analyzing Combustion Instability in Liquid Propellant Rocket Engines. Rep. CPIA Publ. No. 148, Applied Physics Lab., Johns Hopkins Univ., July 1967.
10. Lehmann, G. M.: The Interaction of a Finite Amplitude Pressure Disturbance with a Combustion Region. Rep. JPC-418, TM-66-1, Purdue University, Jan. 1966. (Available from DDC as AD-482941.)
11. Blackshear, Perry L.; Rayle, Warren D.; and Tower, Leonard K.: Study of Screeching Combustion in a 6-inch Simulated Afterburner. NACA TN 3567, 1955.

12. Hayes, Thomas J.; ed.: Elements of Ordnance. John Wiley & Sons, Inc., 1938.

13. Anon.: Military Explosives. Rep. TM 9-1910, Dep. of the Army, and Rep. TO 11A-1-34, Dep. of the Air Force, April 14, 1955.

14. Cook, Melvin A.: The Science of High Explosives. Reinhold Pulb. Corp., 1958.

15. Morrell, Gerald: Rate of Liquid Jet Breakup by a Transverse Shock Wave. NASA TN D-1728, 1963.

16. Dabora, E. K.; Ragland, K. W.; and Ranger, A. A.: Two-Phase Detonations and Drop Shattering Studies. Rep. UM-06324-3-T, University of Michigan (NASA CR-72225), Apr. 1967.

17. Elder, Joseph D.; and Roller, Duane: A Translation of Cranz's Textbook of Ballistics. Vol. II, Part 1, Interior Ballistics. National Defense Research Committee, 1944.

18. Senneff, John M.; and Margante, Paul J.: Combustion Stability Investigation of the LEM Ascent Engine. Proceedings of the Second ICRPG Combustion Conference. CPIA Publ. No. 105, Vol. 1, Applied Physics Lab., Johns Hopkins Univ., May 1966, pp. 23-46. (Available from DDC as AD-484561.)

19. Reardon, F. H.; Crocco, L.; and Harrje, D. T.: Velocity Effects in Transverse Mode Liquid Propellant Rocket Combustion Instability. AIAA J., vol. 2, no. 9, Sept. 1964, pp. 1631-1641.

NASA-Langley, 1969 —— 33 E-4725

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

[illegible] 69120 00903
[illegible] LABORATORY/AFWL/
[illegible] MEXICO 8711[illegible]

[illegible] ACTING CHIEF TECH. LI

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546